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California Institute of Technology

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# The Origin of Mars' South Polar Massive CO<sub>2</sub> Ice Deposit from Co-Evolution with Mars' Atmosphere

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Ehlmann<sup>1,2</sup>, and Paul Hayne<sup>3</sup>

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Institute of Technology, <sup>3</sup>University of Colorado, Boulder

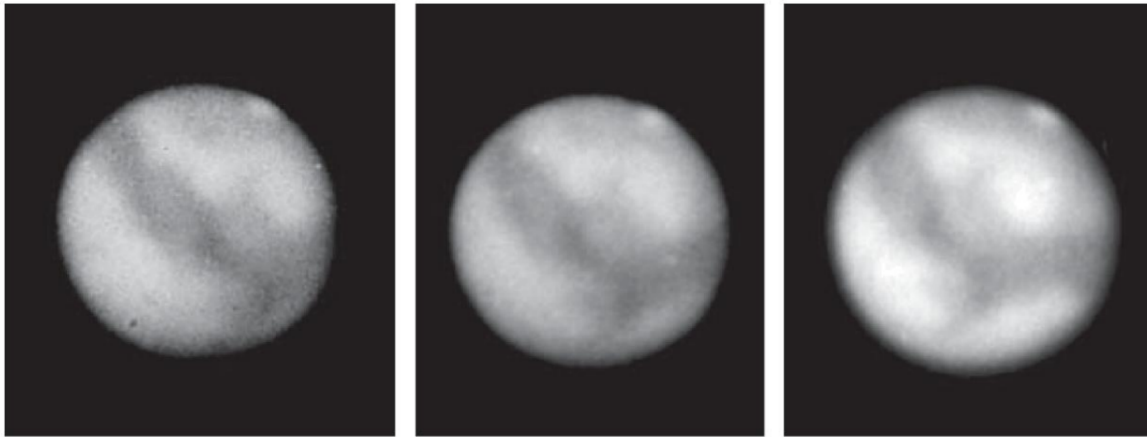
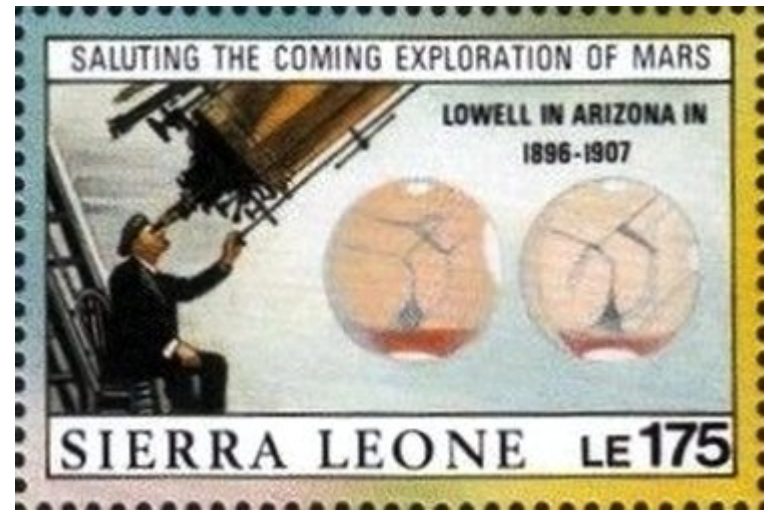
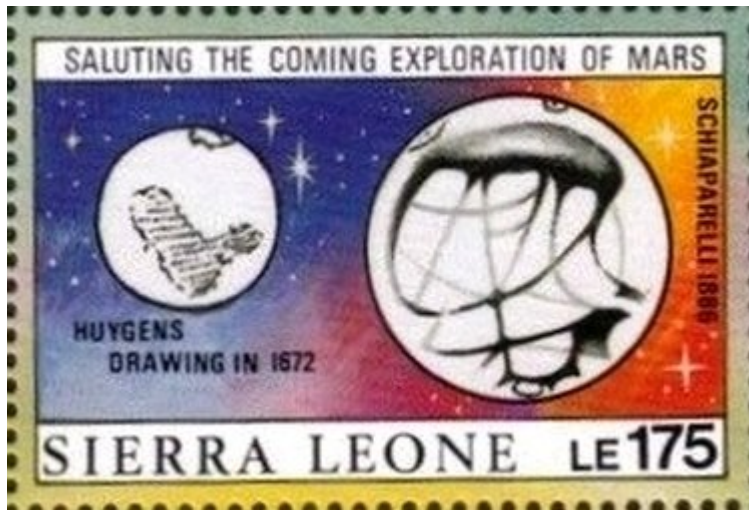
Postdoc Seminar Series

2019.06.06



# History

# The Beginning of Mars Polar Observation



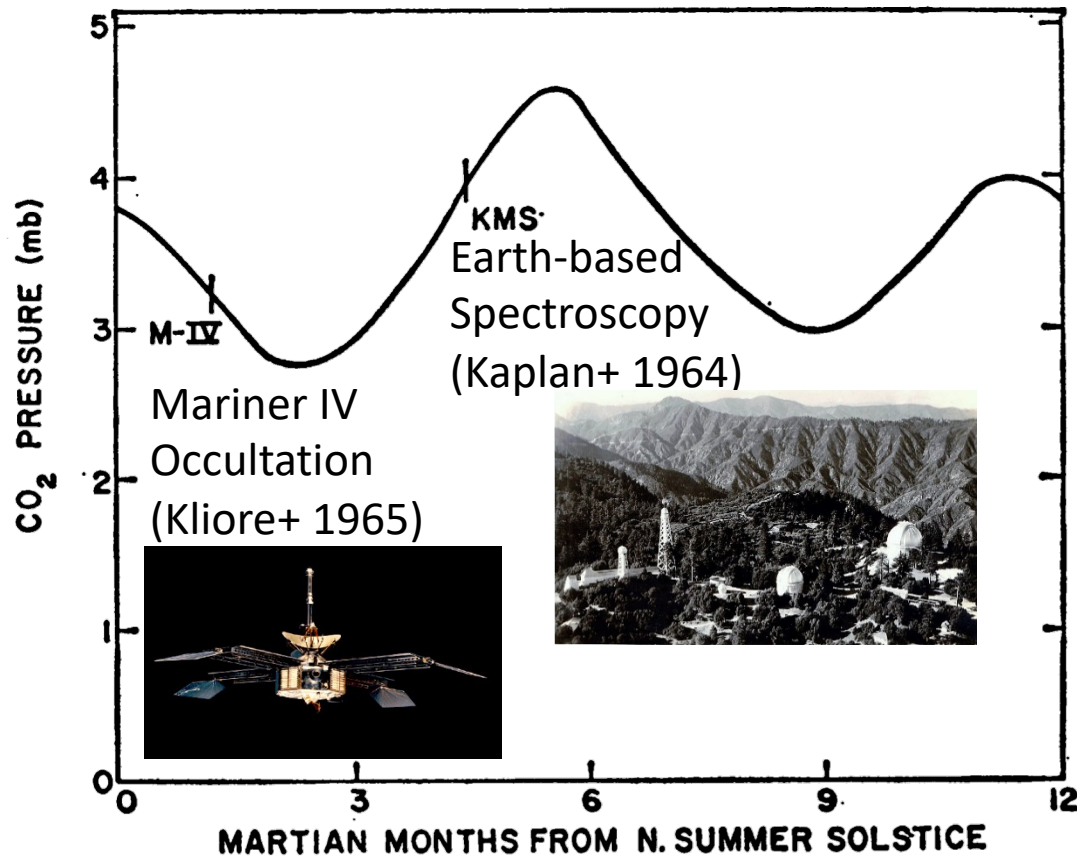
**Figure 4.** Composite images of Mars on 1909 September 27 at 12h 35m, 13h 35m and at 14h 20m (times in Greenwich Mean Astronomical Time [GMAT] reckoned from noon, as was usual at the time). Each image represents the superposition of several images from the same plate, in order to reduce the graininess and enhance the subtle details.

1909: First Pic du Midi  
photographs of Mars  
(Dollfus, 2010)

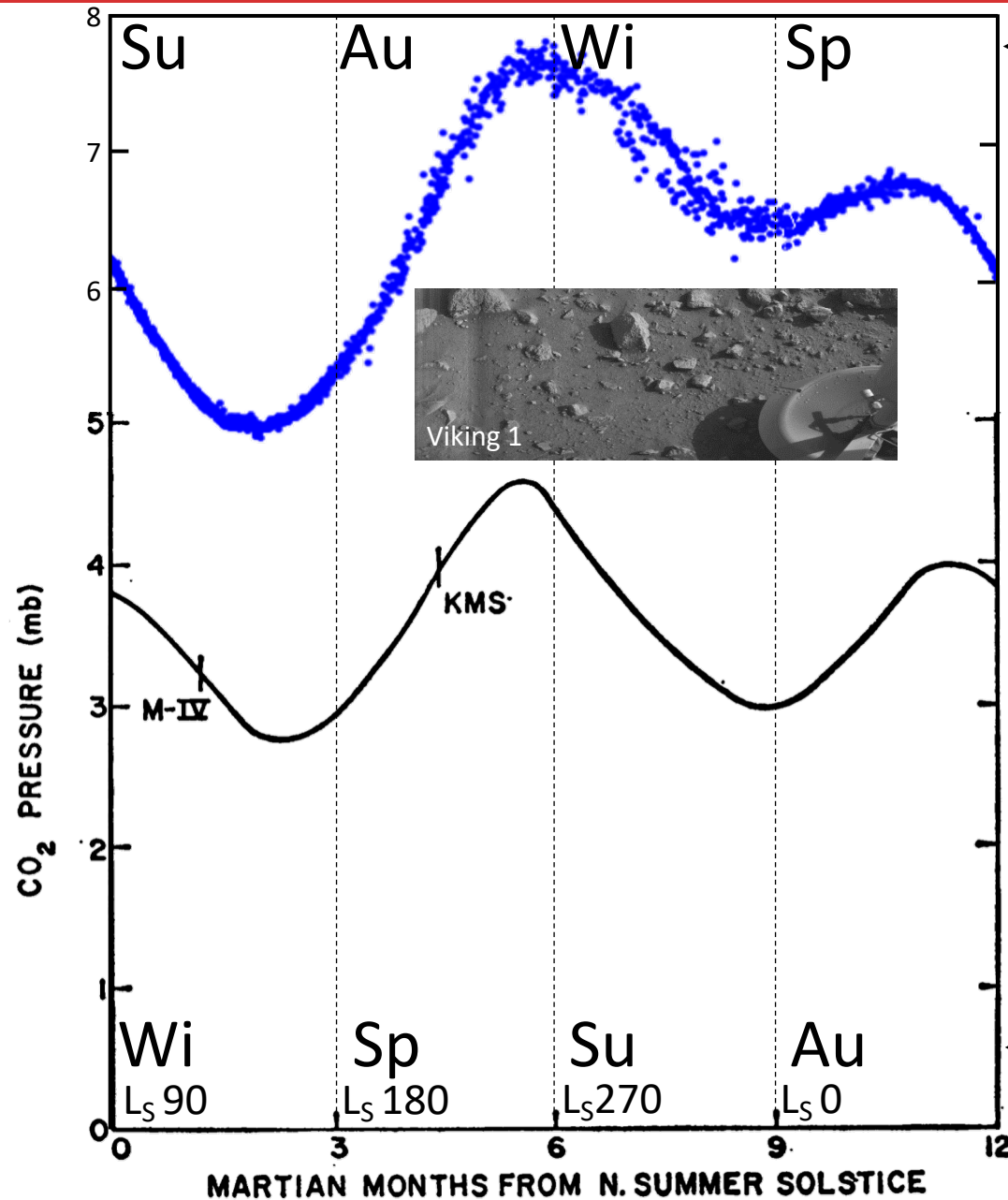
# At the Dawn of Robotic Exploration



# Leighton and Murray (1966)

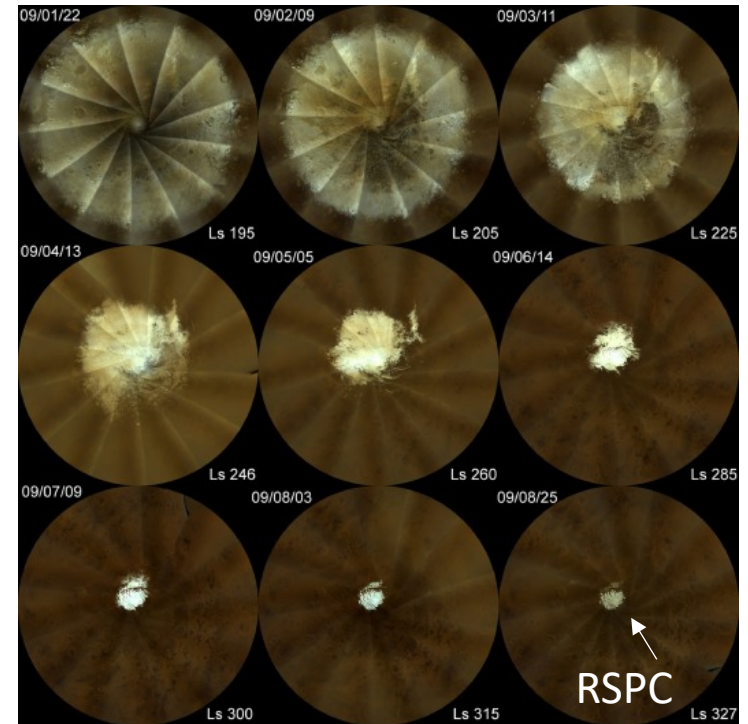


# Mars' Seasonal CO<sub>2</sub> Cycle



← Northern Seasons

## South Polar Seasonal CO<sub>2</sub>

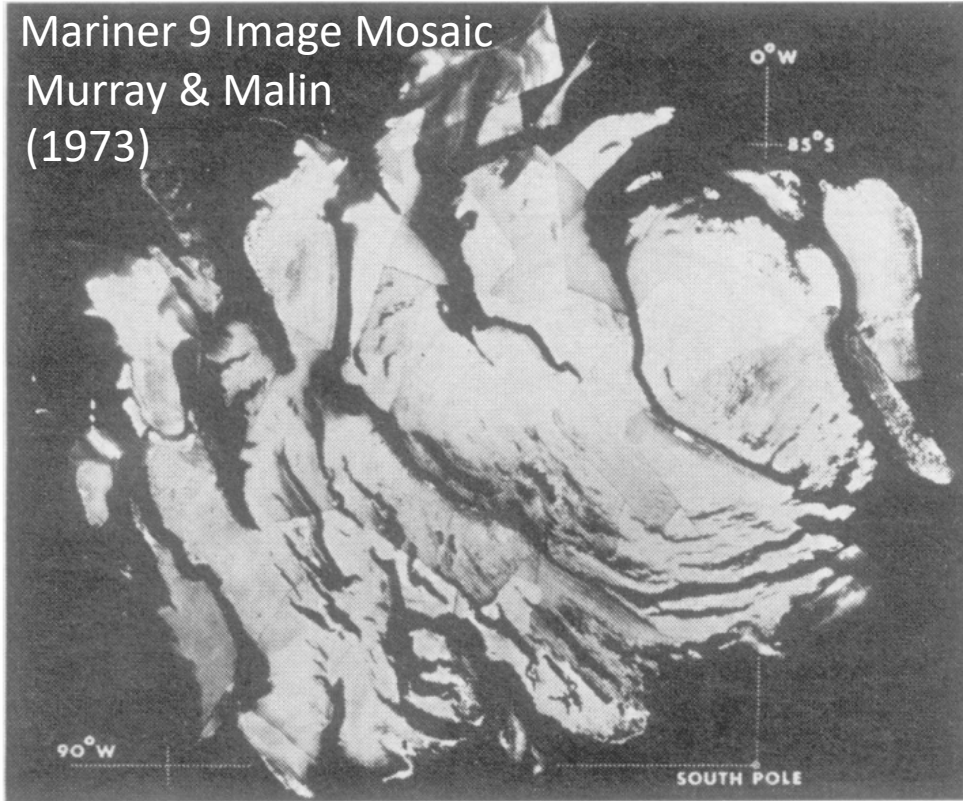


*Calvin+ (2015)*

← Southern Seasons

# What is the RSPC?

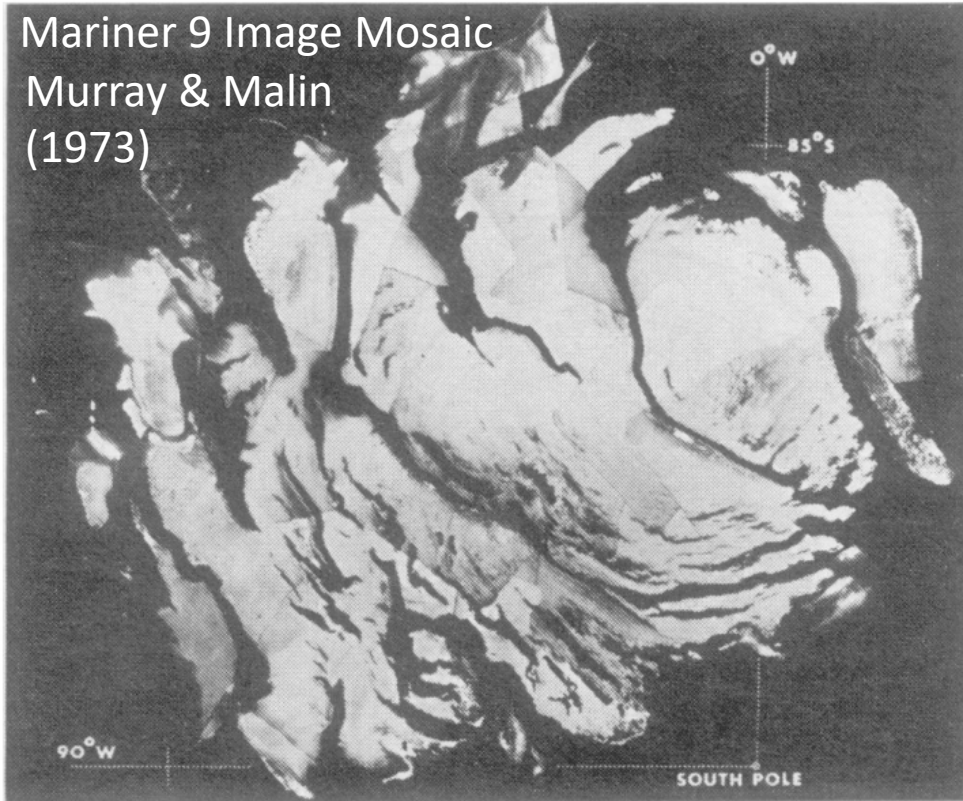
Mariner 9 Image Mosaic  
Murray & Malin  
(1973)



- “CO<sub>2</sub> ice could not survive in contact with low-albedo material.”
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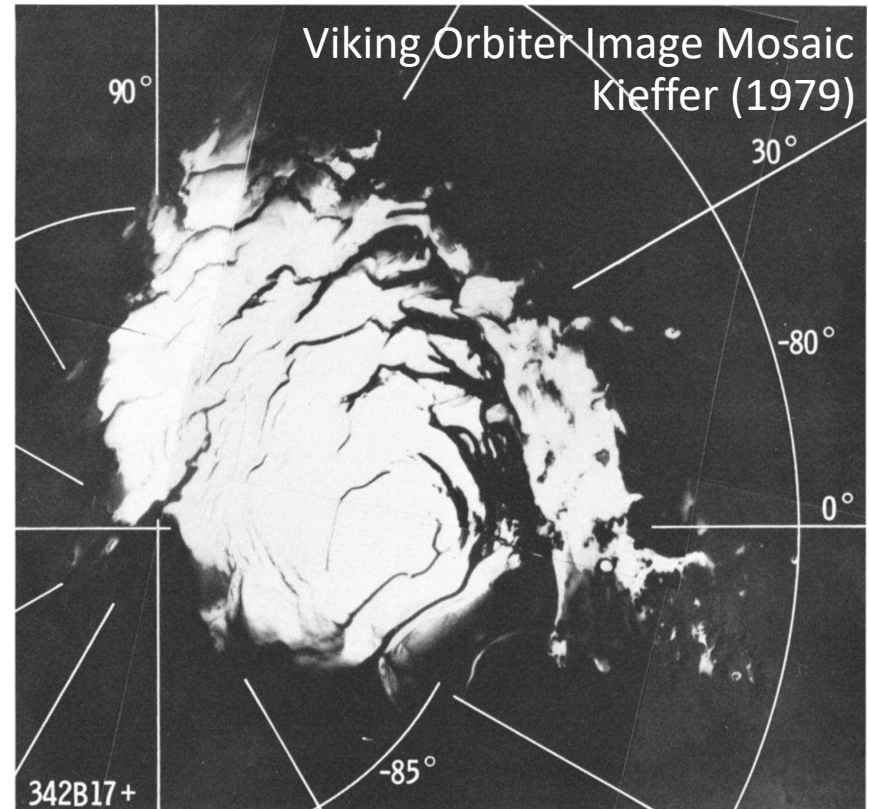
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Viking Orbiter Image Mosaic  
Kieffer (1979)

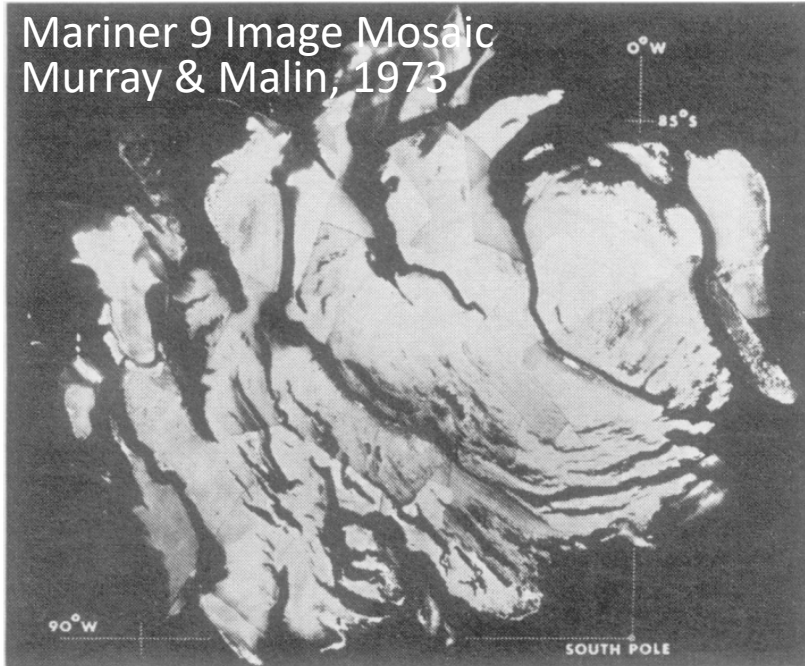


- “Throughout the summer, the polar frost remained at the temperature of solid CO<sub>2</sub>.”
- “Thus Mars appears to have a residual polar cap of CO<sub>2</sub> in the south and one of H<sub>2</sub>O in the north.”

# A Puzzle: Why CO<sub>2</sub> at the South Pole?

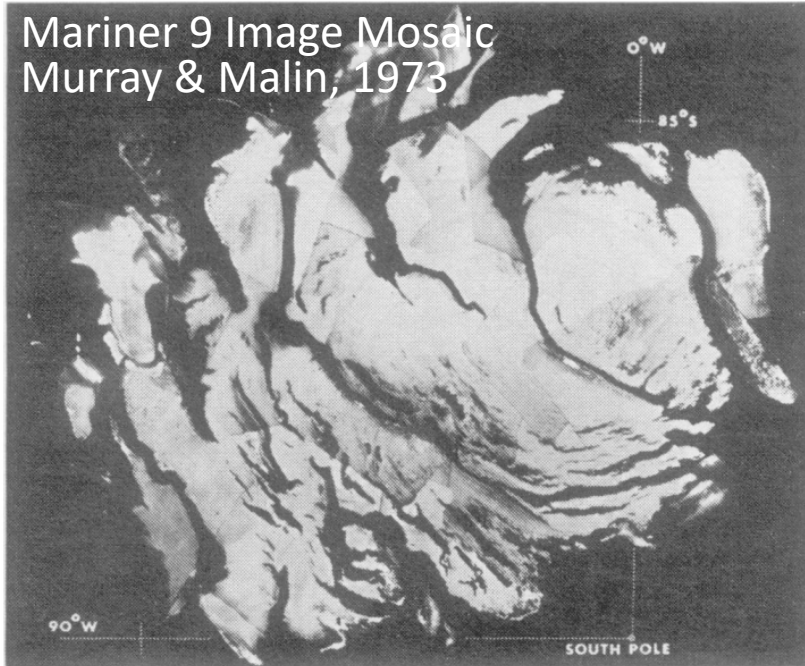
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Mariner 9 Image Mosaic  
Murray & Malin, 1973



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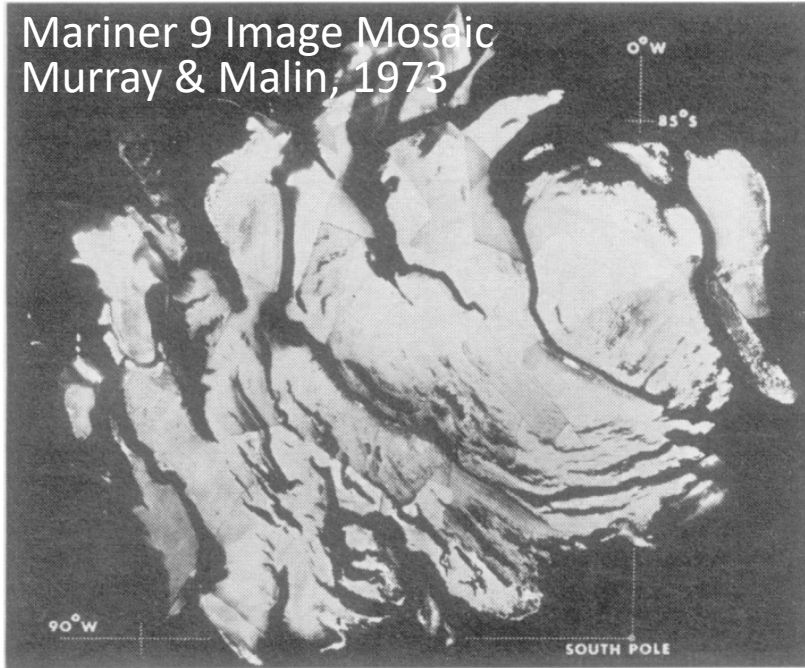
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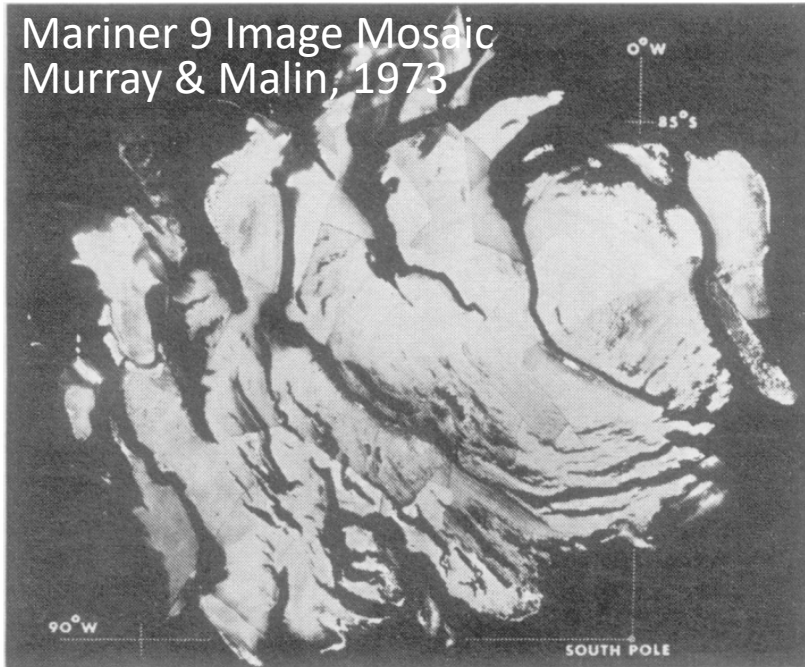
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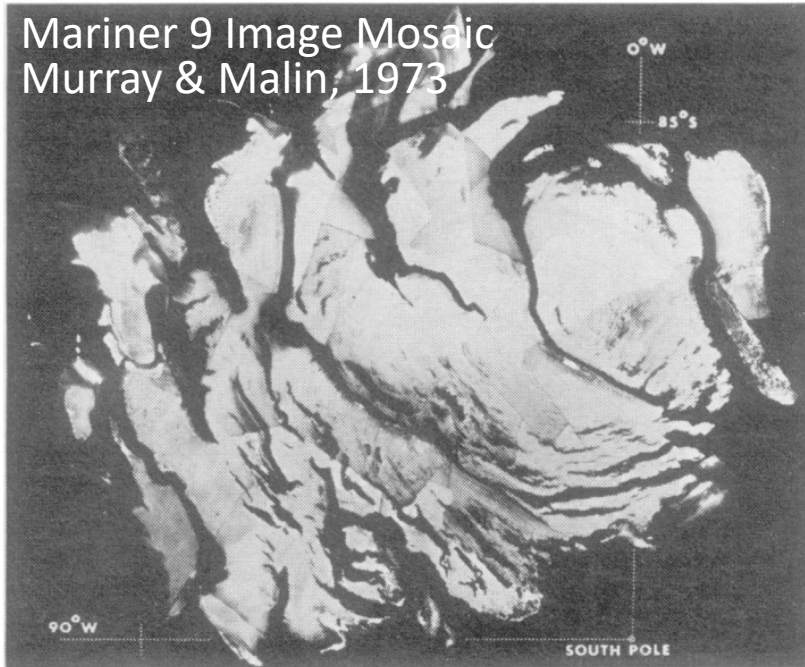
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- “Hence, solid CO<sub>2</sub> deposits in the south would be out of equilibrium and would gradually be transferred to the north...in well under 1000 years.”

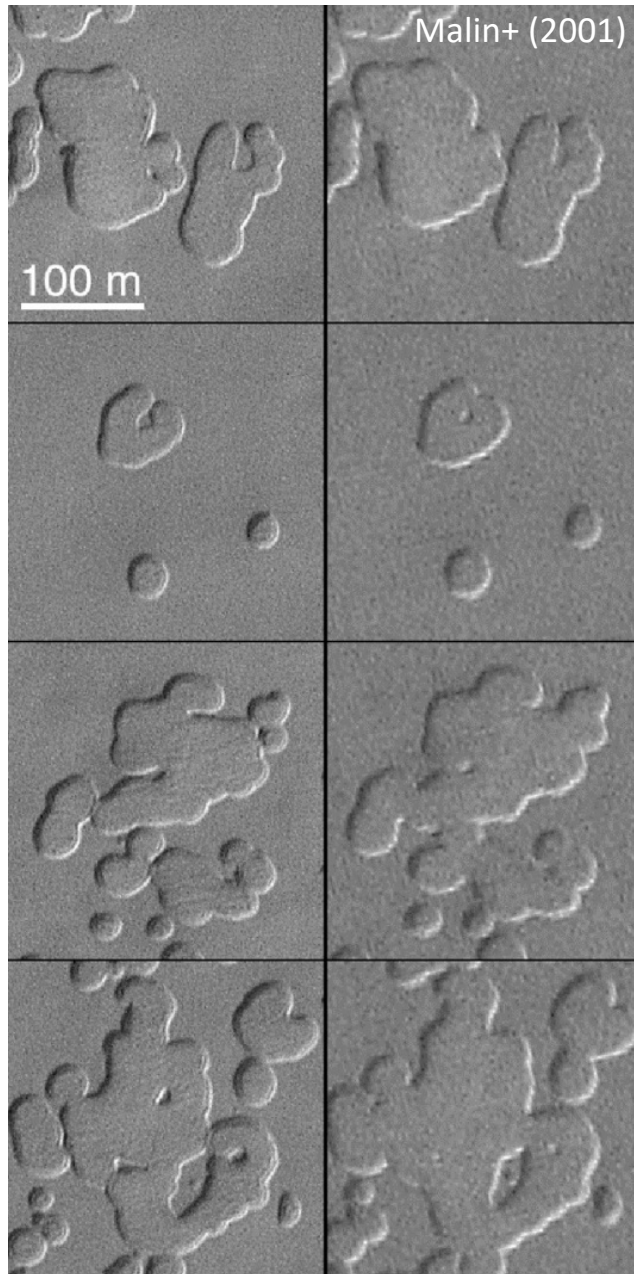
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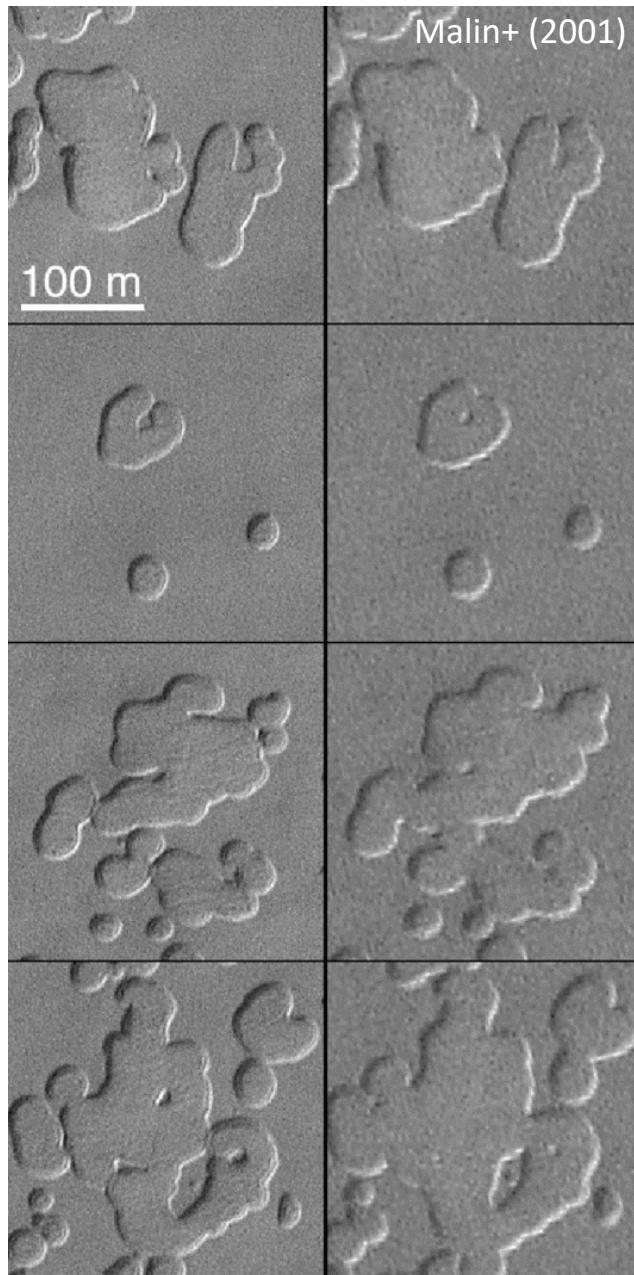
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- “There is no reason to suppose a permanent CO<sub>2</sub> southern cap would be at a systematically lower temperature than the northern one.”
- “Hence, solid CO<sub>2</sub> deposits in the south would be out of equilibrium and would gradually be transferred to the north...in well under 1000 years.”
- “Excess solid carbon dioxide is probably present [buried] in the north residual cap.”

# Is the CO<sub>2</sub> ice is disappearing?



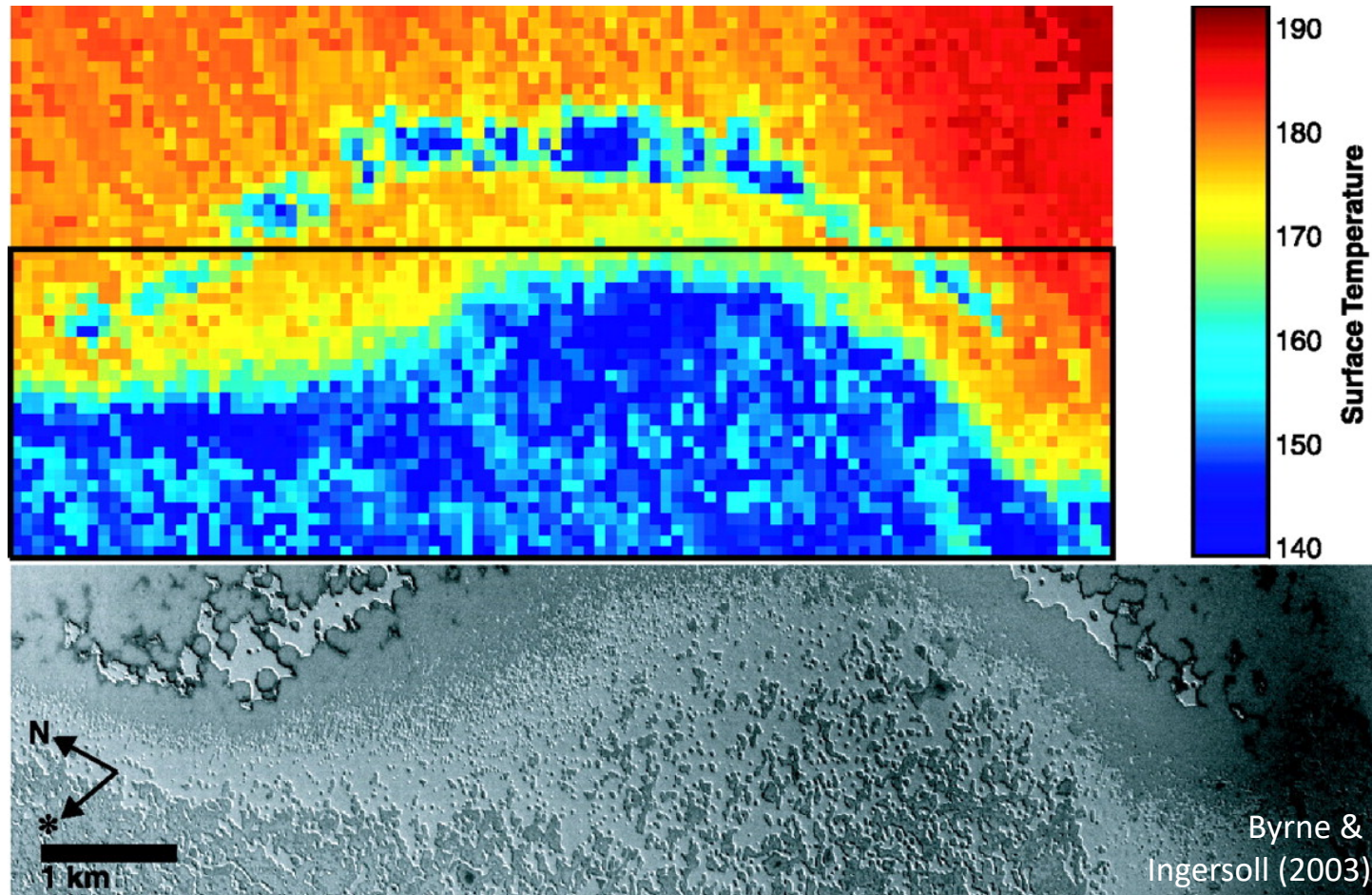
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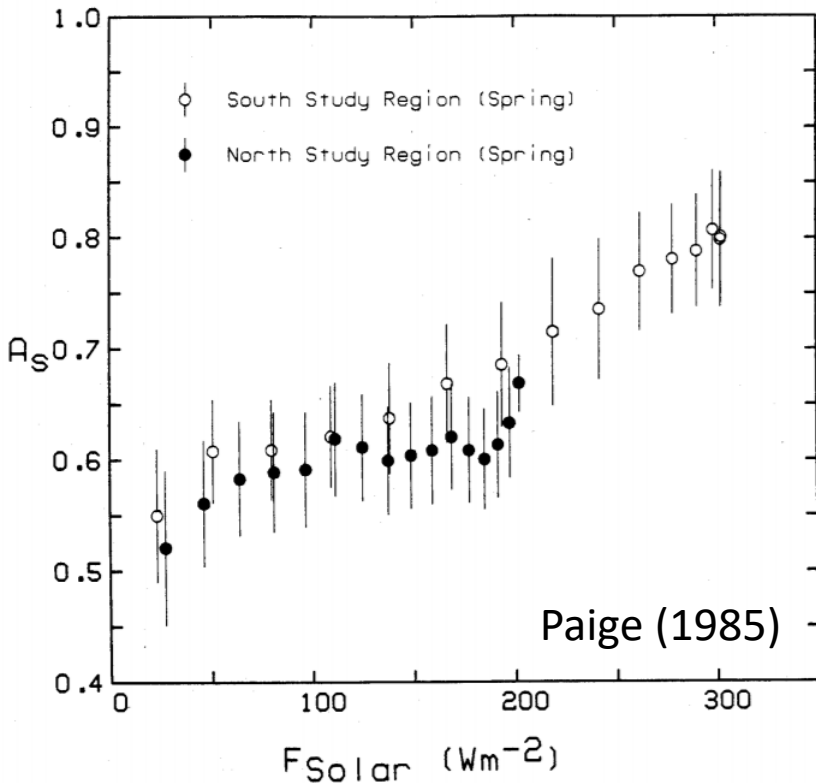
- “The erosion implies that this reservoir is not in equilibrium with the present environment and that global climate change is occurring on Mars.”
- “These and other observations suggest that the present martian environment is neither stable nor typical of the past.”

# Is the CO<sub>2</sub> ice is disappearing?



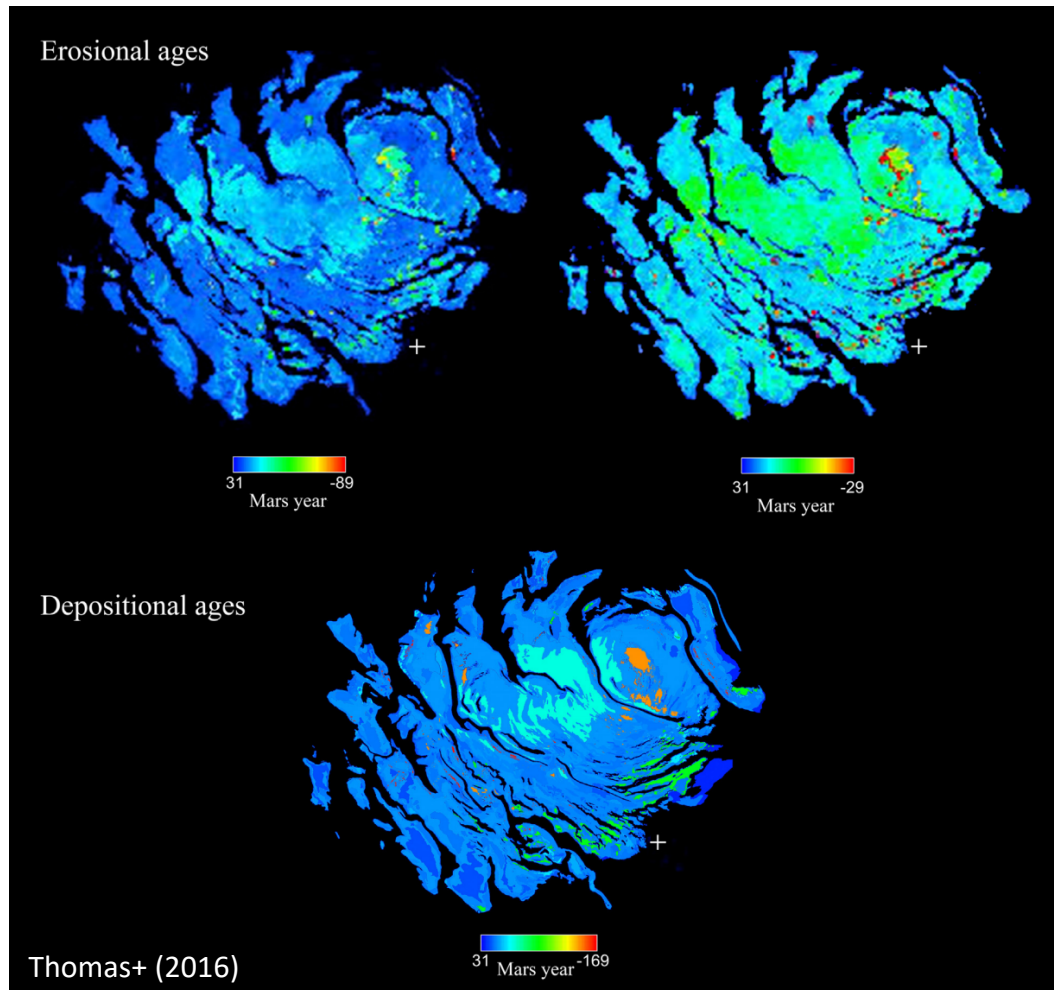
- “The implication is that both polar caps are predominantly composed of H<sub>2</sub>O ice, although a veneer of CO<sub>2</sub> ice covers the south cap.”
- “The upper 8-m layer will be removed in a few martian centuries, [but likely] has some rejuvenation mechanism.”

# Difficult to Model the RSPC



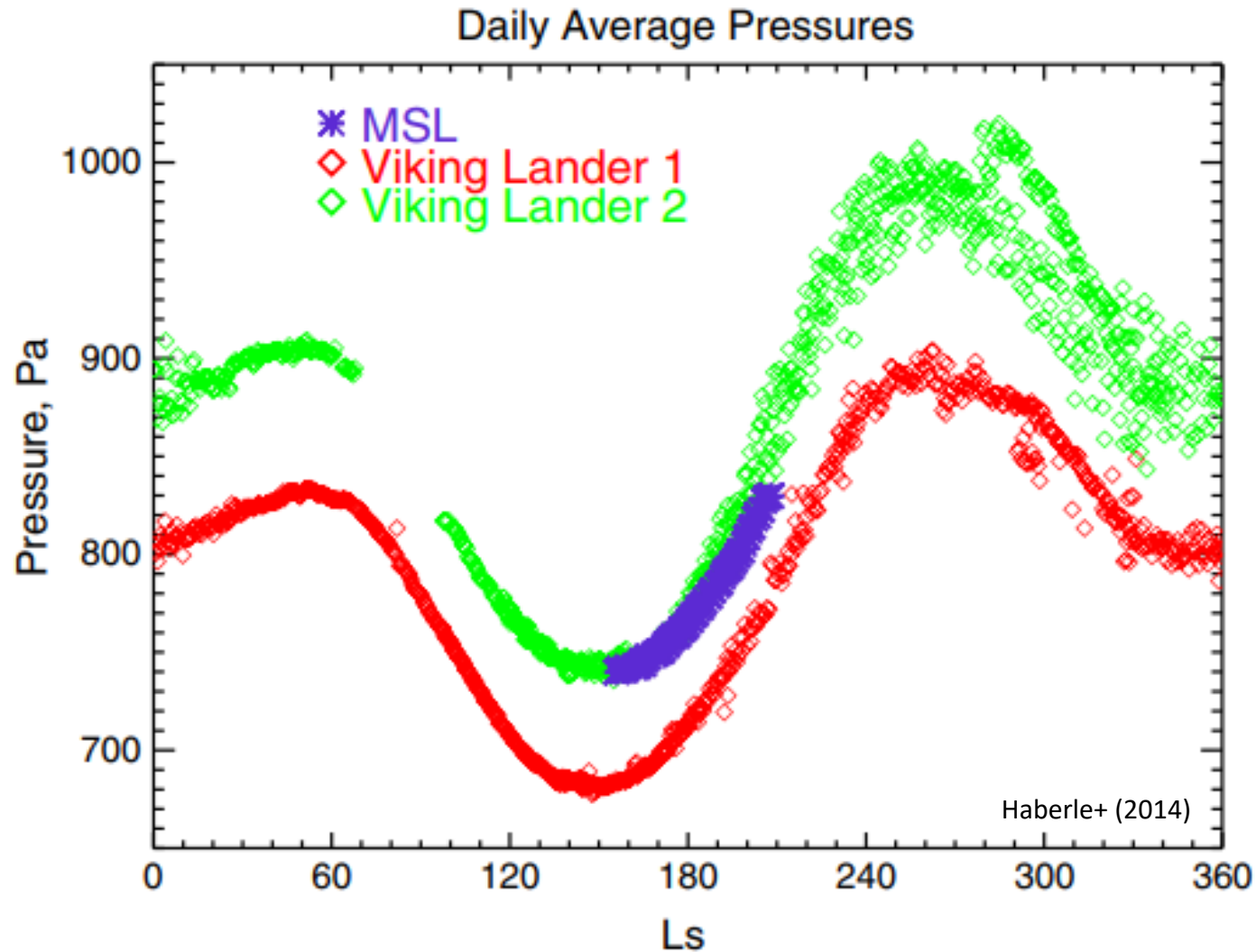
- “Models conventionally treat surface CO<sub>2</sub> ice using constant ice albedos and emissivities, such an approach fails to predict the existence of a perennial cap.” – *Guo+ 2010*
- “If the CO<sub>2</sub> ice albedo follows the [currently observed] relationship ... we expect that the CO<sub>2</sub> residual ice caps [should] swap hemispheres as the argument of perihelion progresses.” – *Guo+ 2010*

# Or maybe not?



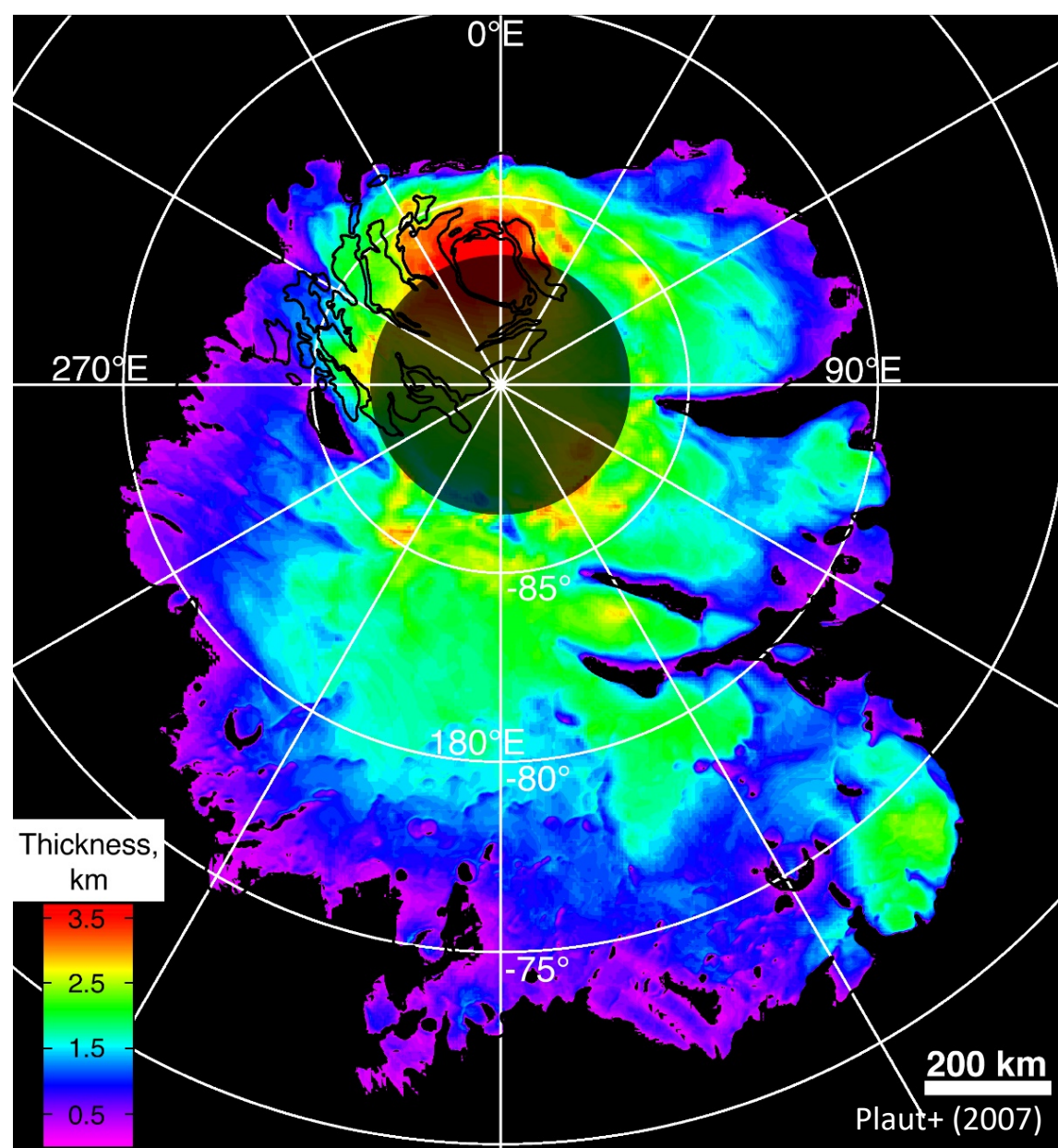
“We find the mass balance in Mars years 9–31 to be  $-6$  to  $+4$  km<sup>3</sup> per martian year, or roughly  $-0.039\%$  to  $+0.026\%$  of the mean atmospheric CO<sub>2</sub> mass per martian year.”

# Or maybe not?



“When compared to Viking Lander 2 data, the REMS daily average pressures show no evidence yet for the 1–20 Pa increase expected from the possible loss of CO<sub>2</sub> from the south polar residual cap.”

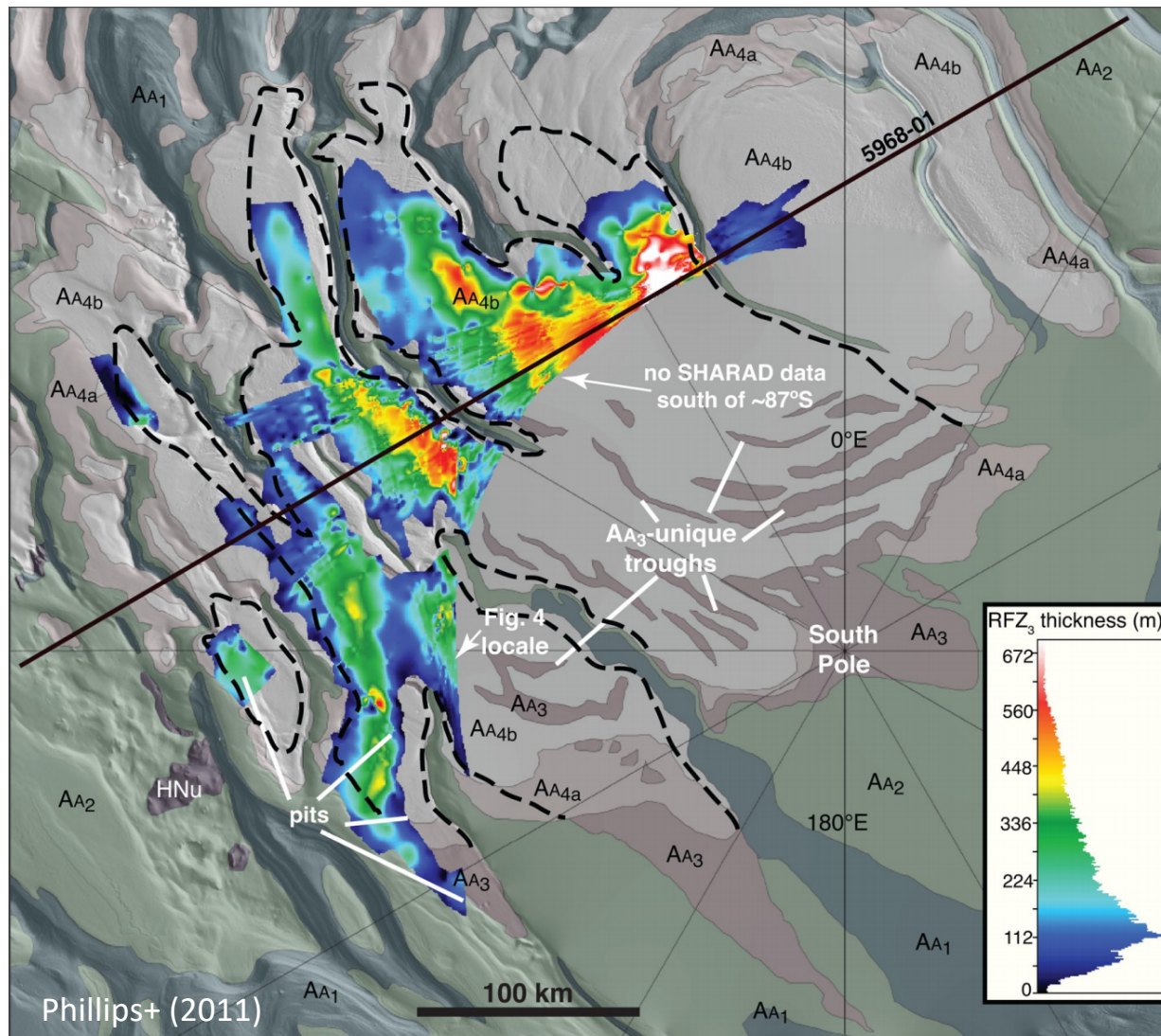
# In 2010: RSPC is only known perennial CO<sub>2</sub>



“It would have to be considered an extraordinary accident if the total CO<sub>2</sub> released over the history of Mars and now available at the surface should just exactly equal that required for the formation of the observed annual caps: a small proportion less and hardly any annual caps would form at all; any larger amount would be in the form of buried solid.”

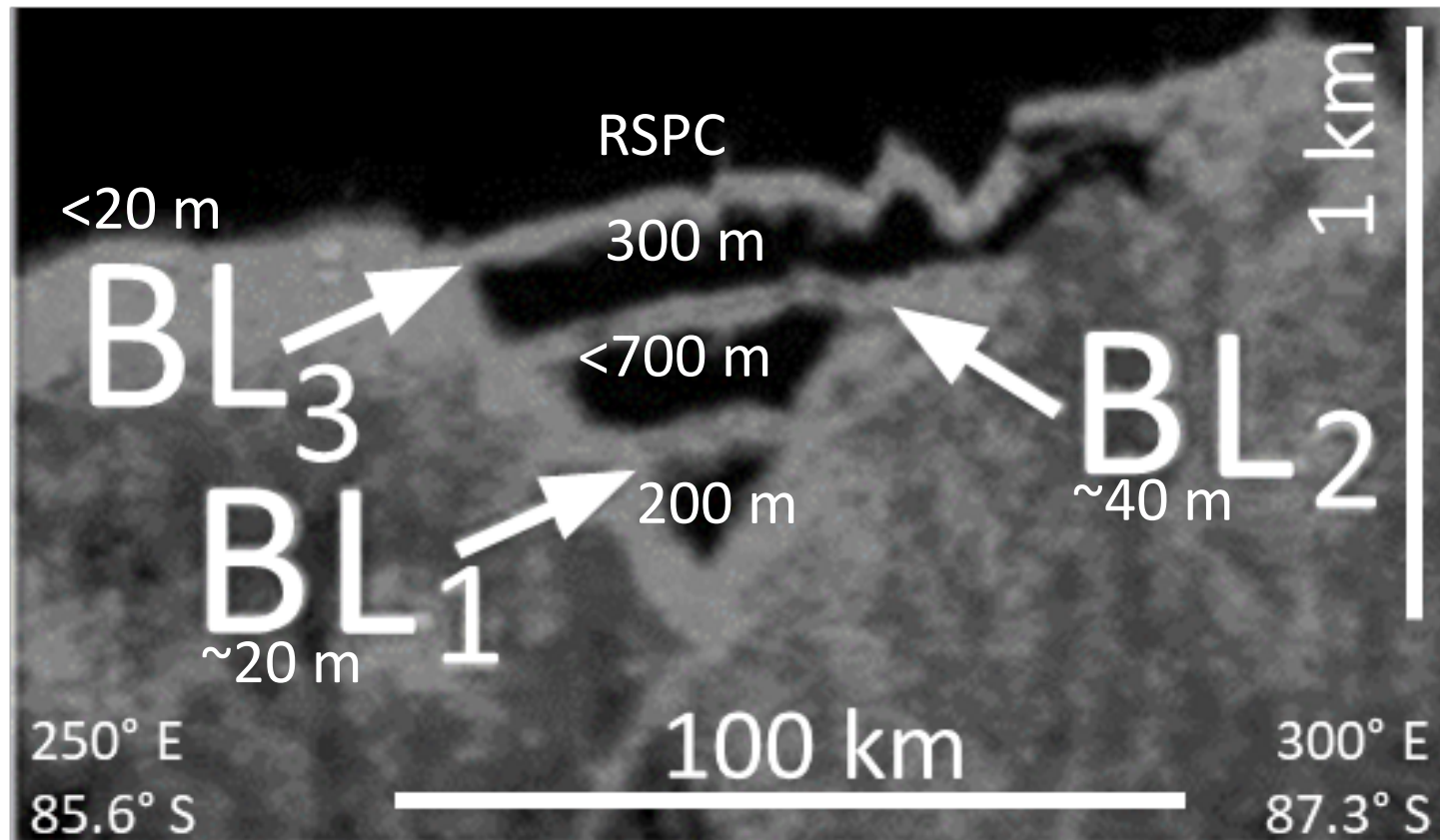
—Murray and Malin (1973)

# A Massive CO<sub>2</sub> Ice Deposit (MCID)!



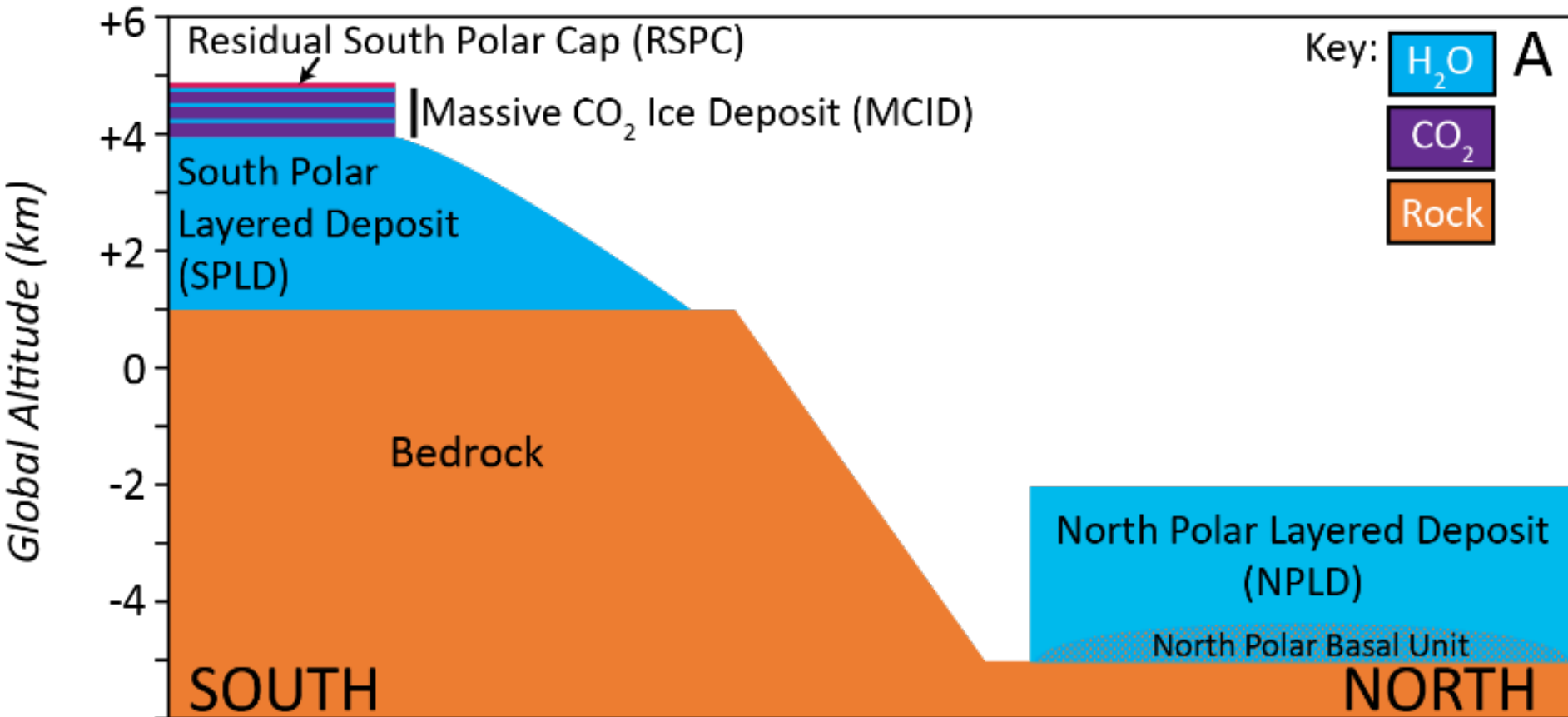
“If released into the atmosphere at times of high obliquity, the CO<sub>2</sub> reservoir would increase the atmospheric mass by up to 80%.”

# The MCID has layers



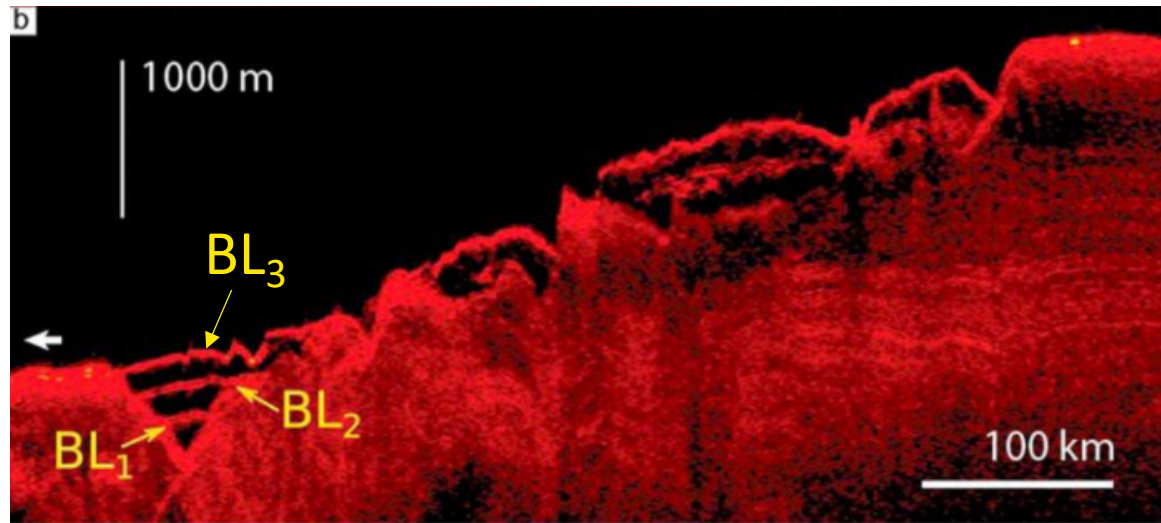
“We find three distinct CO<sub>2</sub> subunits, each capped by a bounding layer (BL).”  
--*Bierson+ 2016*

# Schematic Polar Stratigraphy

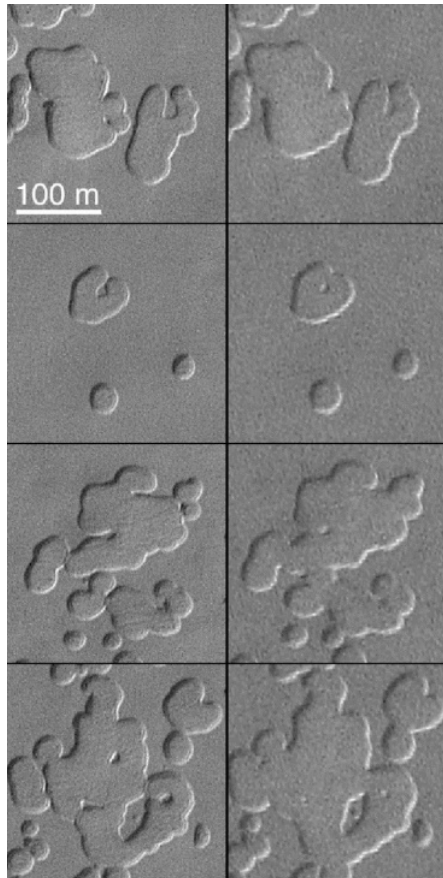


# Outstanding Questions

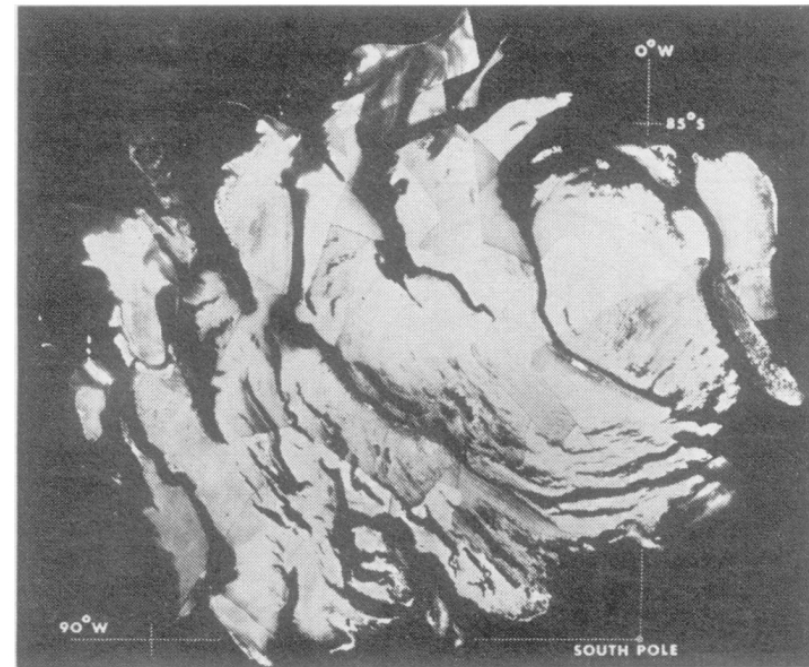
1. How was the massive CO<sub>2</sub> deposit emplaced with its observed stratigraphy?



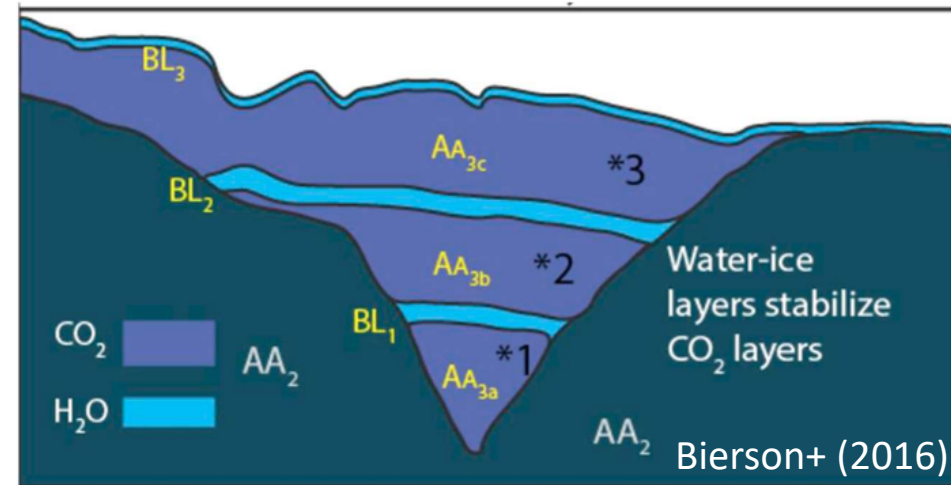
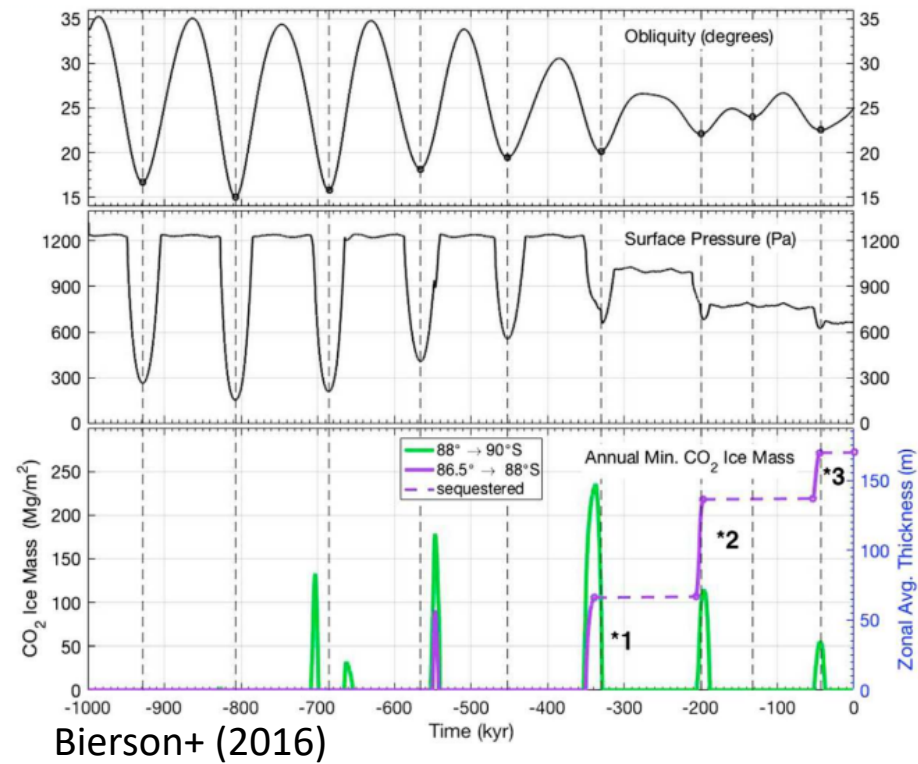
2. Why does the RSPC exist?



3. Will the permanent CO<sub>2</sub> always be at the south pole (not the north or both)?

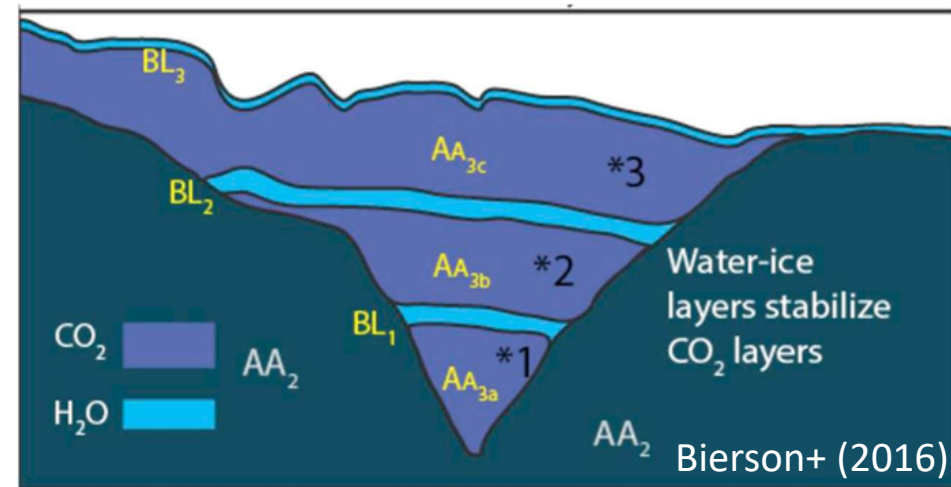
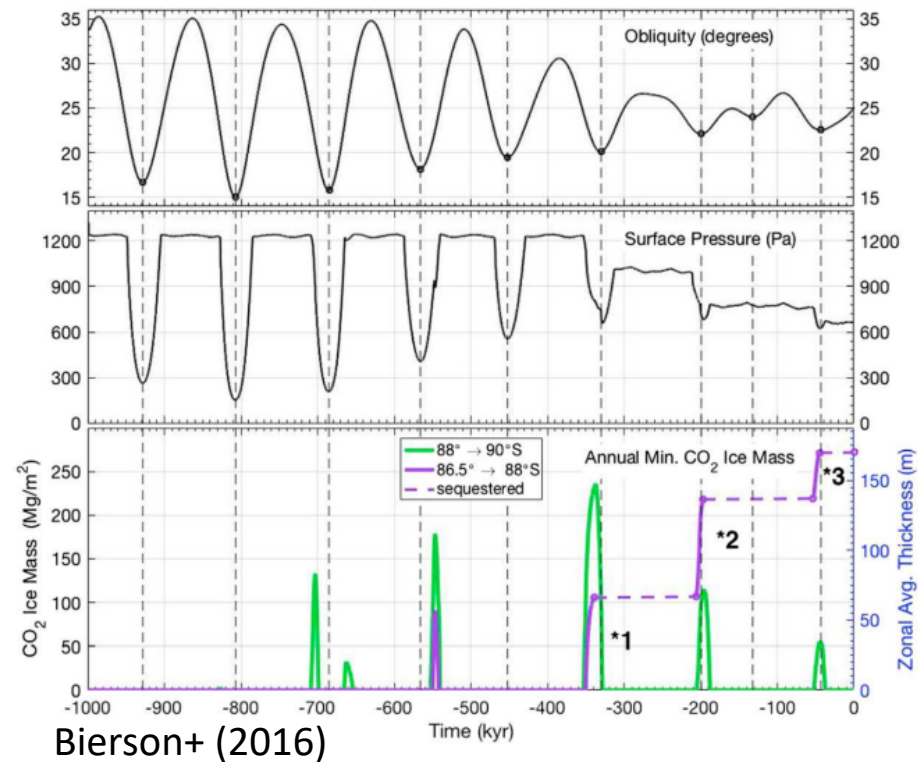


# Previous model of MCID emplacement



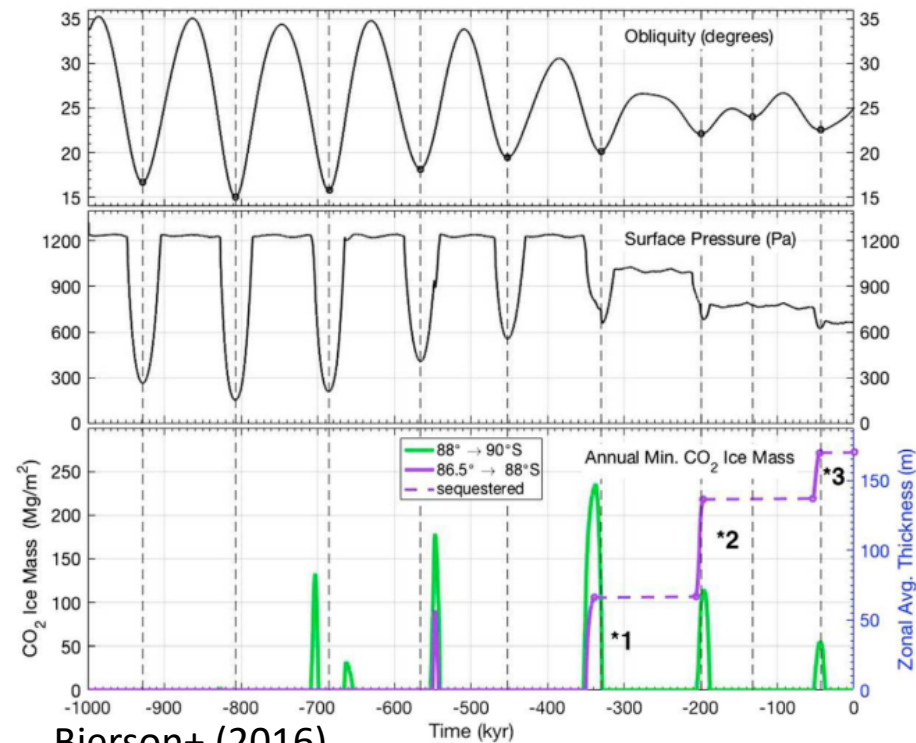
- “CO<sub>2</sub> ice is deposited over much of the poles during low obliquity periods.”

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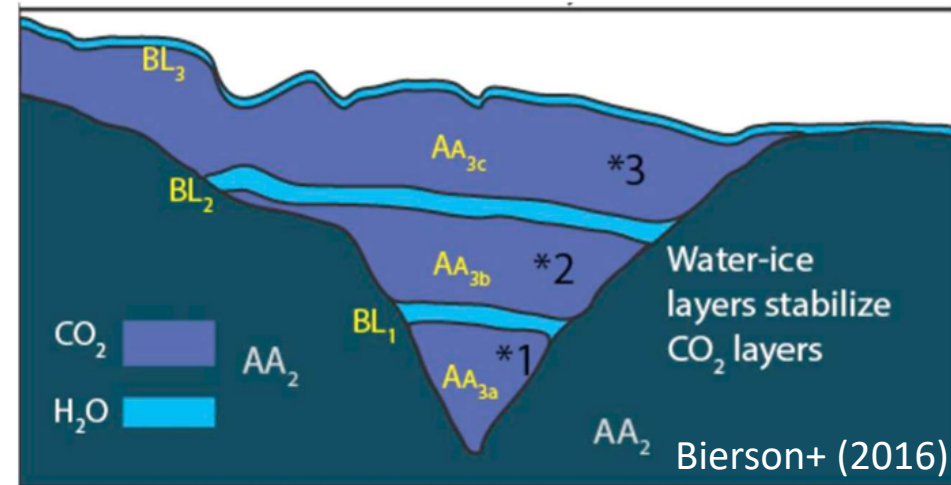


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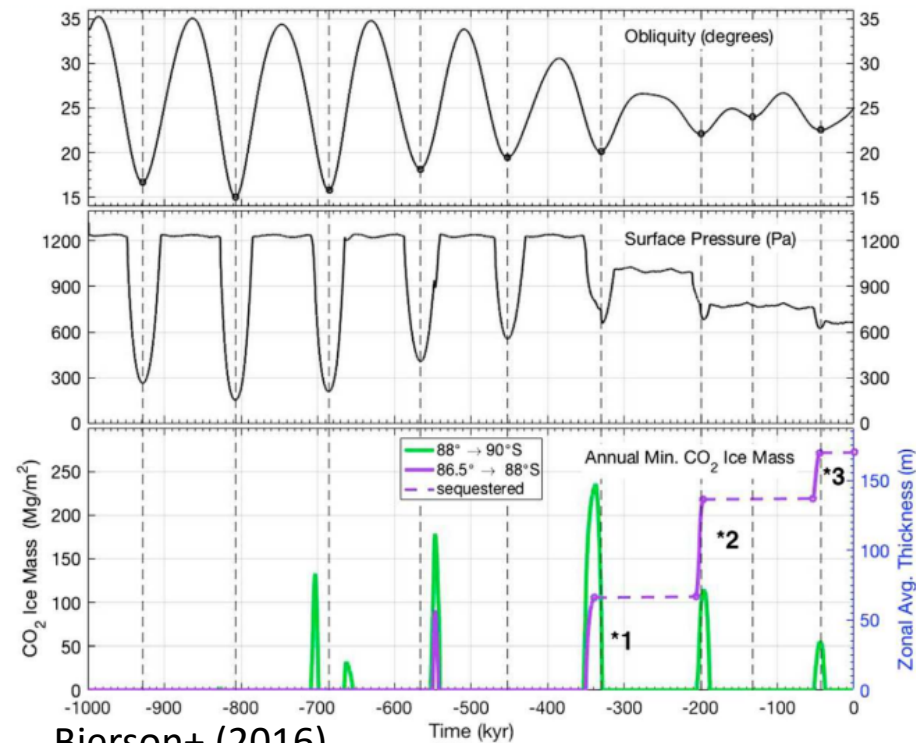
Bierson+ (2016)



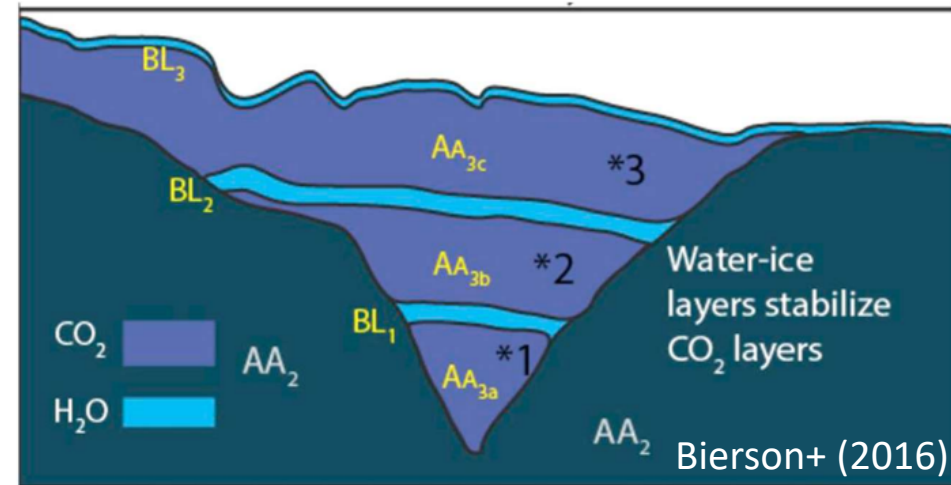
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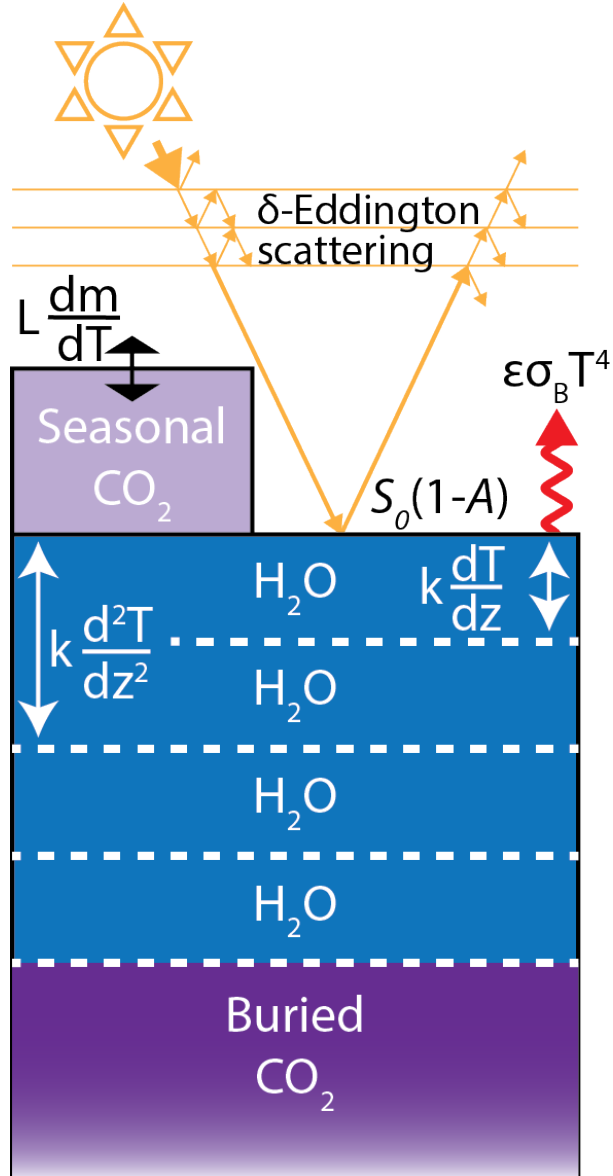
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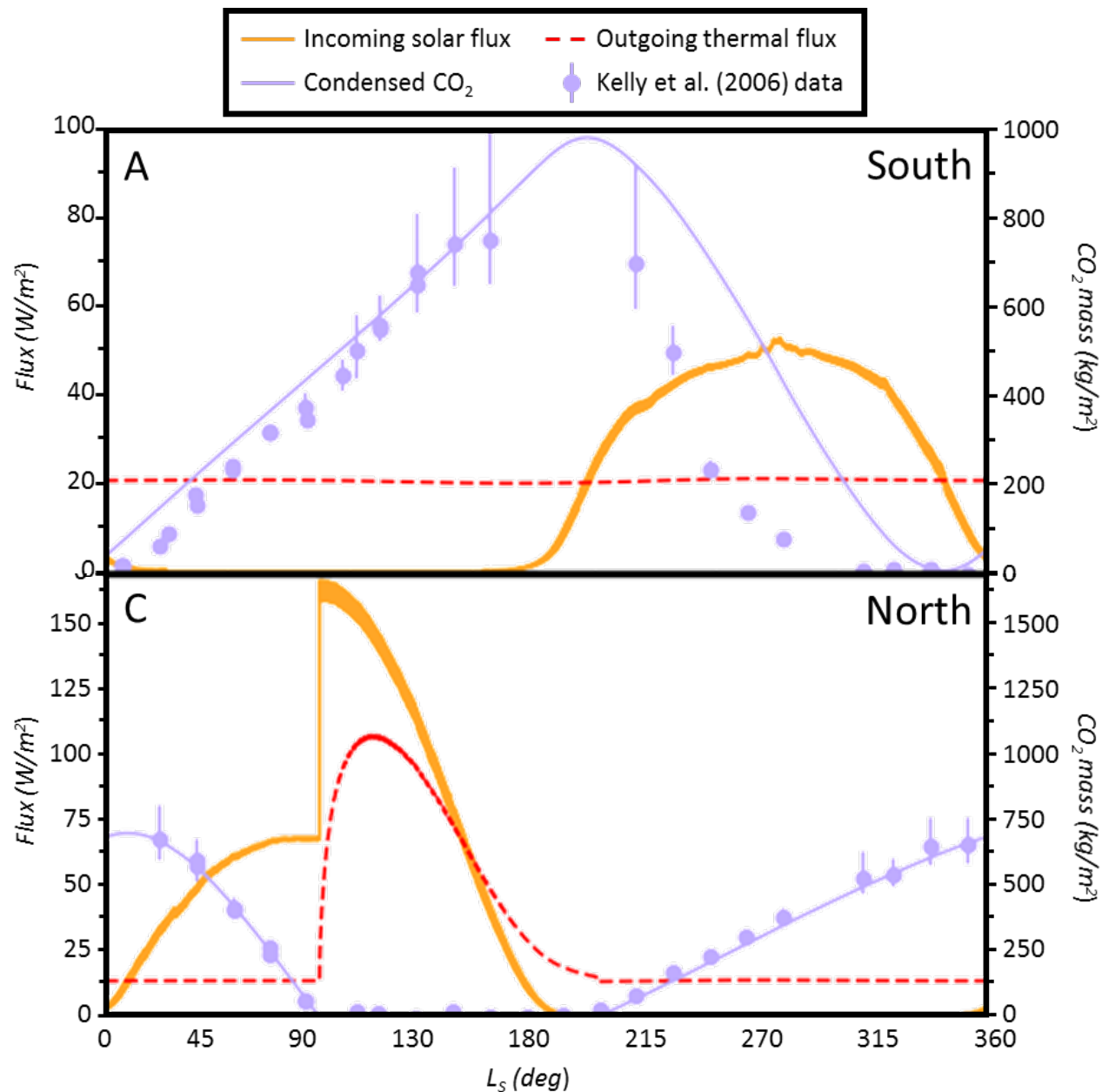
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- “Our base model does not sequester the [CO<sub>2</sub>] ice, and it returns to the atmosphere at the end of each period of high obliquity.”
- “However, the presence of the [massive CO<sub>2</sub>] unit requires some mechanism to stabilize and protect the deposit in periods of high obliquity.”

# Methods

# Our Model Set-Up

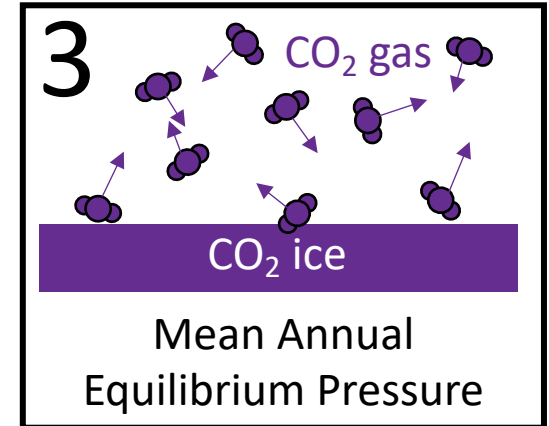
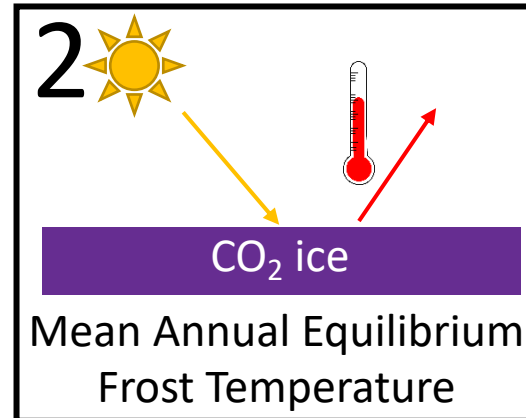
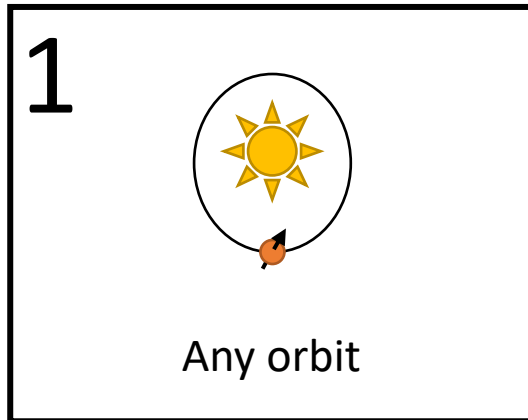


# Model the Modern CO<sub>2</sub> Cycle



# Our Model Set-Up

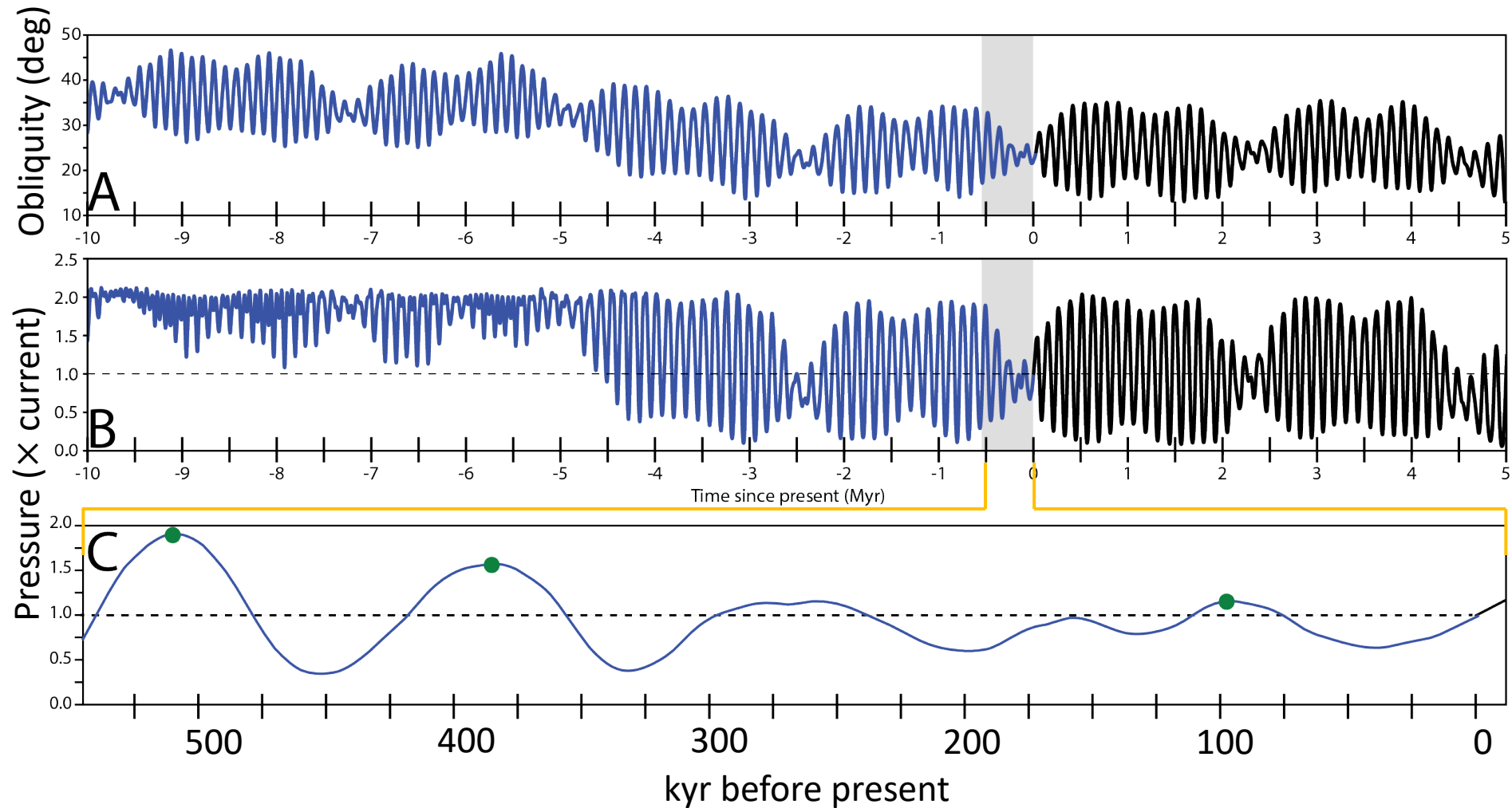
## 1D Energy balance:



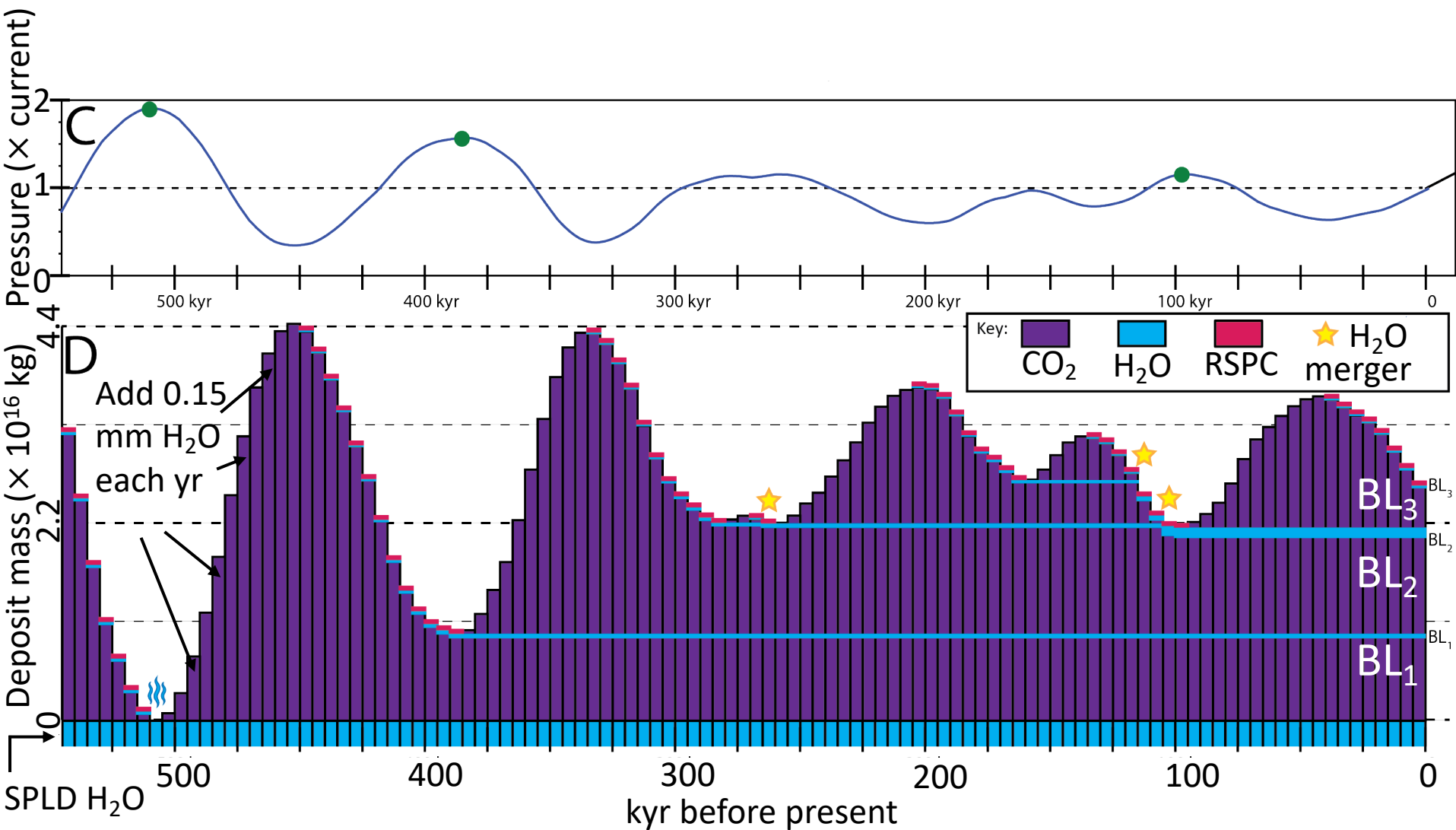
- Emissivity: 0.8, Albedo:  $A_{CO_2} = 0.532 + 0.511 \times \cos(\theta_{solar})$
- CO<sub>2</sub> mass: atmosphere + deposit =  $5.4 \times 10^{16}$  kg
- Account for elevation change from finite cap thickness, with MCID area = RSPC area ( $8 \times 10^{10}$  m<sup>2</sup>)
- Different set-up compared to previous models: Vapor contact between MCID and atmosphere at all times.

Results!

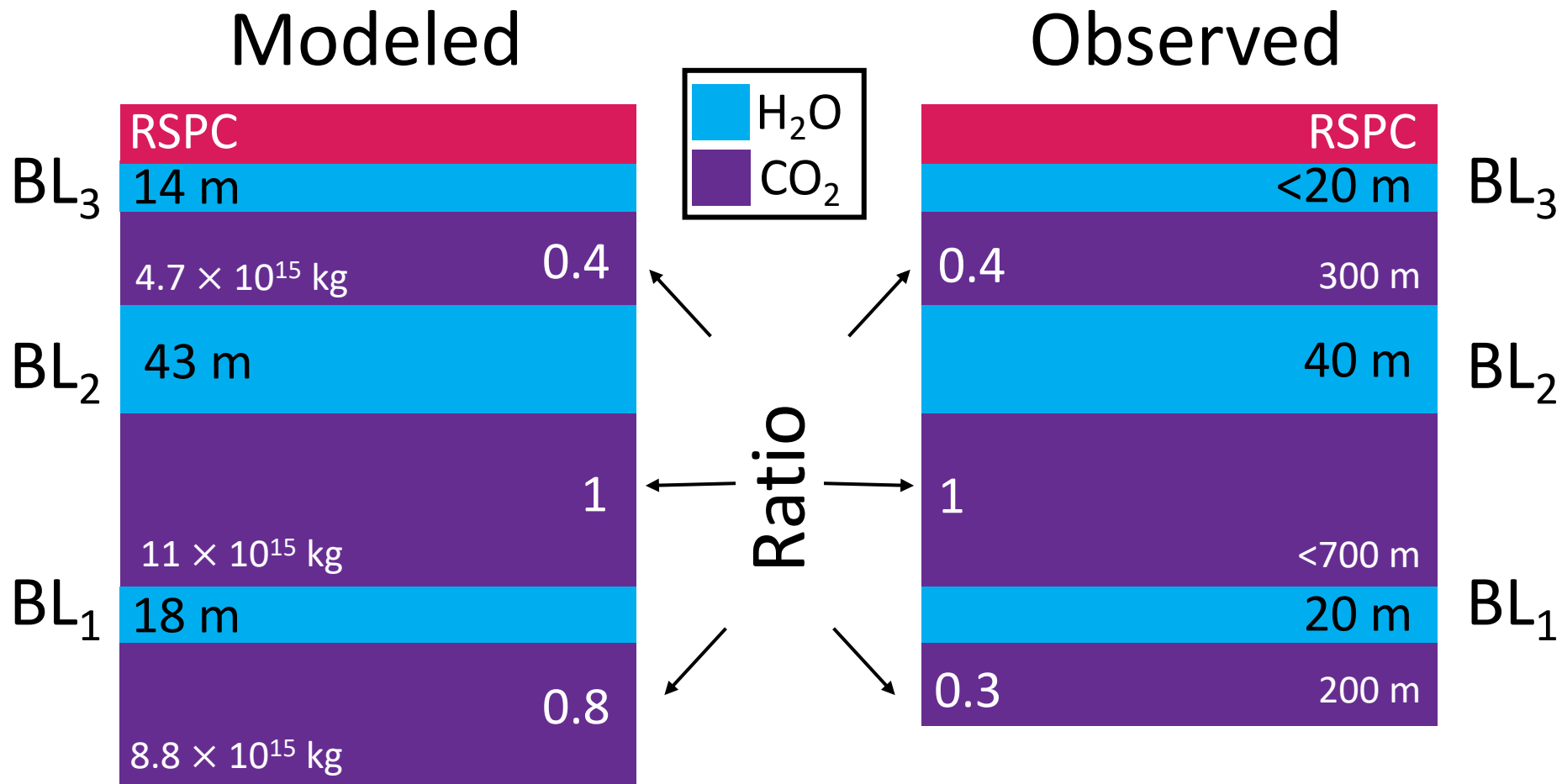
# Mars' Pressure History



# MCID Stratigraphic History



# Modeled & Observed MCID Stratigraphy



**CO<sub>2</sub> layer mass depends on amplitude of obliquity maxima,**  
**H<sub>2</sub>O BL thickness depends on time between obliquity maxima**

Comparison to observation

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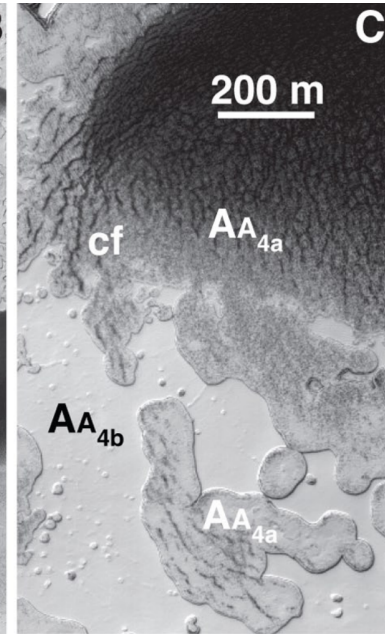
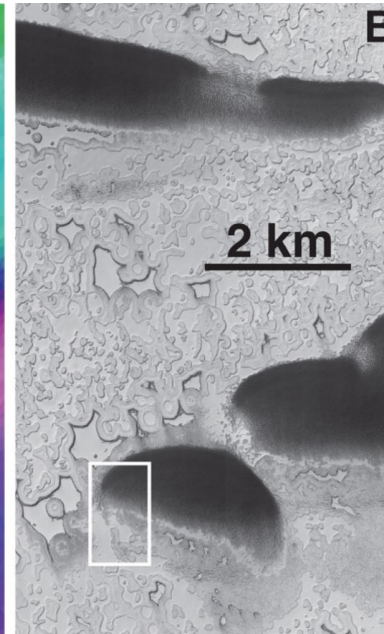
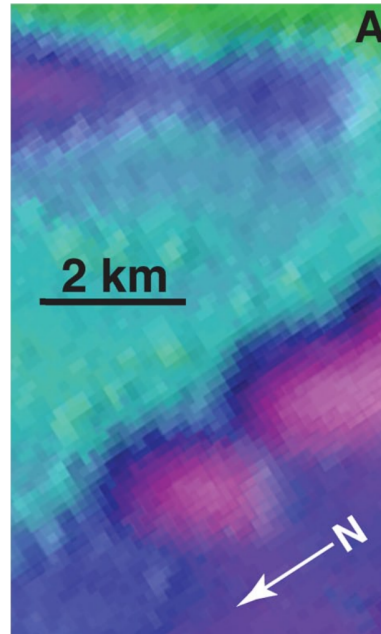
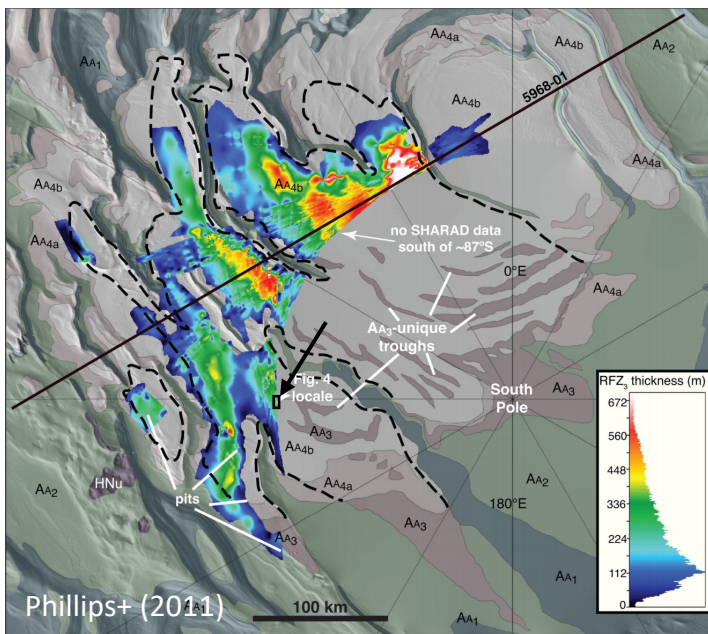
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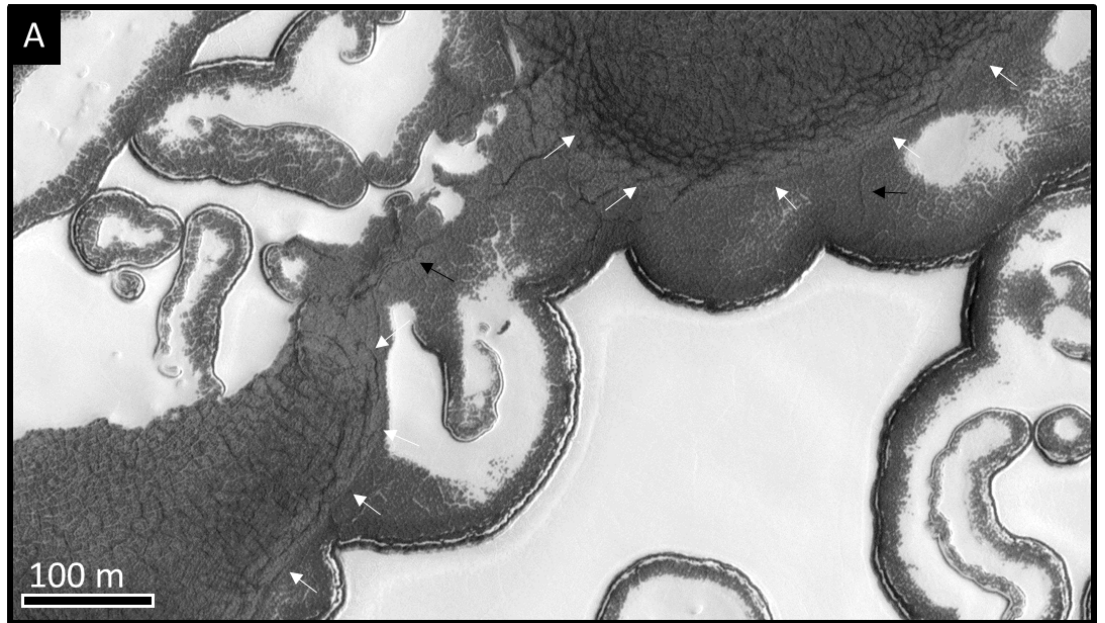
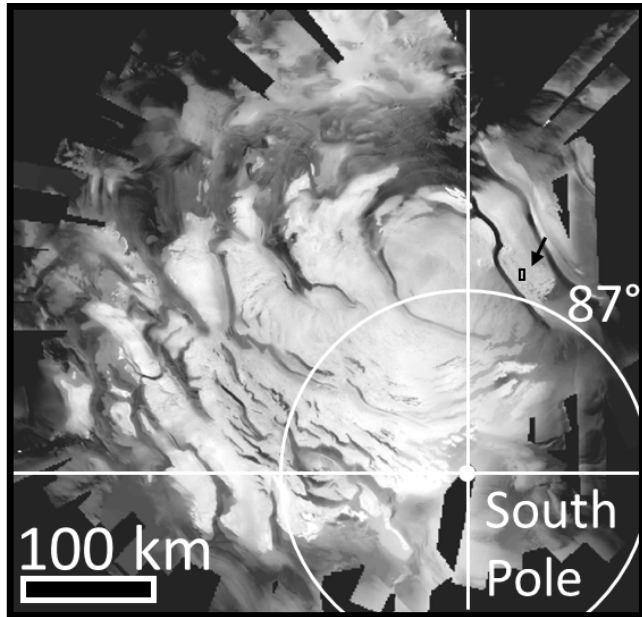
*Thus, a scum layer of dark (low albedo) material may be buried beneath a topmost layer of frost, but as soon as this topmost layer is removed, the dark dust [or H<sub>2</sub>O ice] will heat up and any CO<sub>2</sub> beneath it will escape.” –Murray and Malin (1973)*

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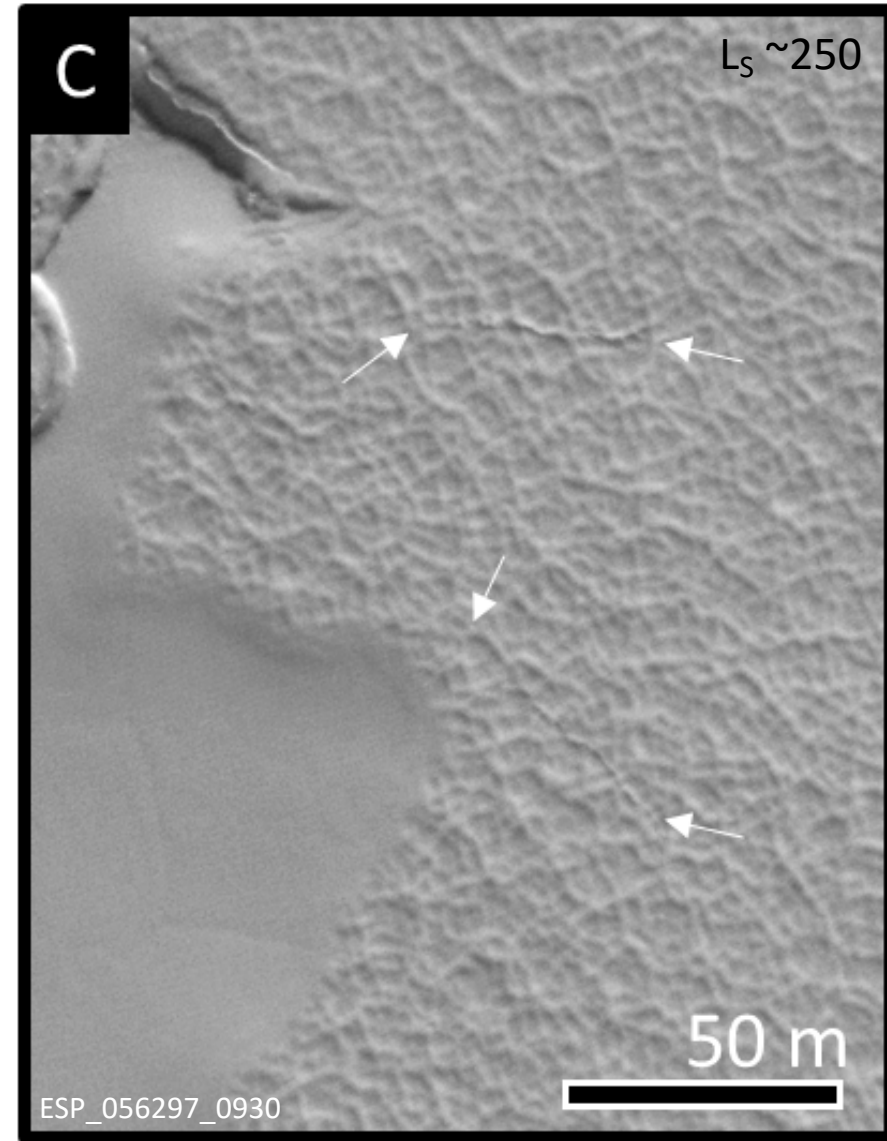
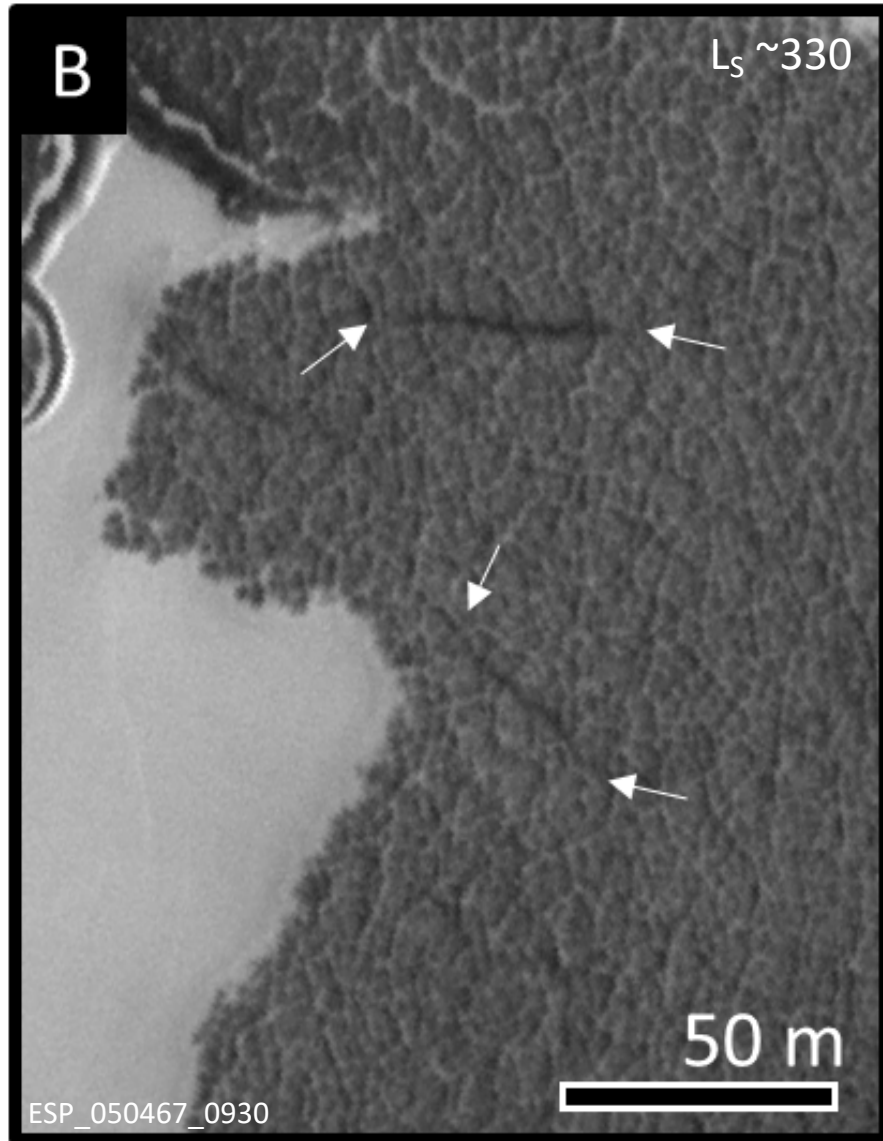
- “All of these smaller troughs, depressions, and pits appear to result from erosion and removal of unit A<sub>A3</sub> [the massive CO<sub>2</sub> deposit], with a strong component of sublimation and collapse.”
- “The fracturing, not found in other SPLD units, may be a response to continuing unit A<sub>A3</sub> [MCID] sublimation after the pits had first formed.” – *Phillips+ 2011*

# Does H<sub>2</sub>O seal in CO<sub>2</sub>?

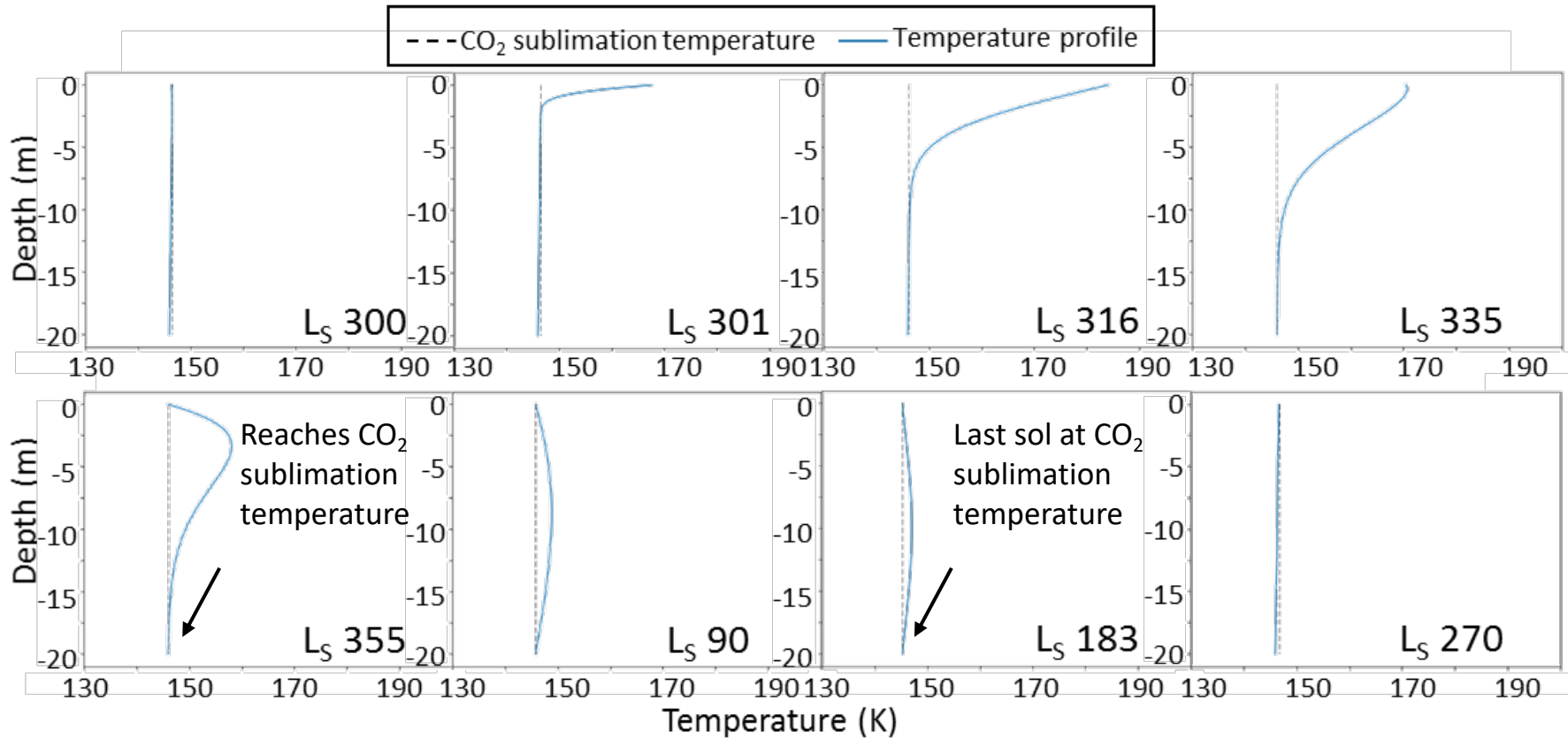


ESP\_050467\_0930

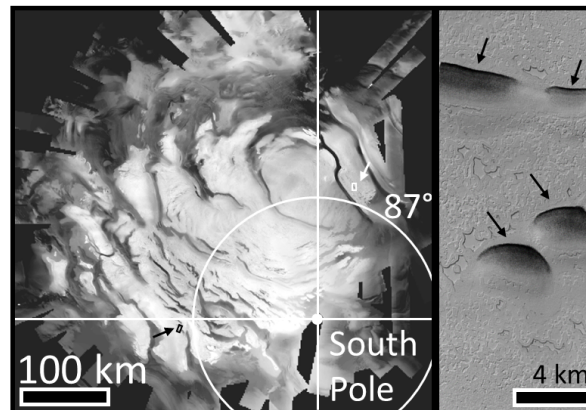
# Does H<sub>2</sub>O seal in CO<sub>2</sub>?



# Does H<sub>2</sub>O insulate CO<sub>2</sub>?



Modern-day model run,  
condensed CO<sub>2</sub> forced  
to zero at L<sub>S</sub> 300

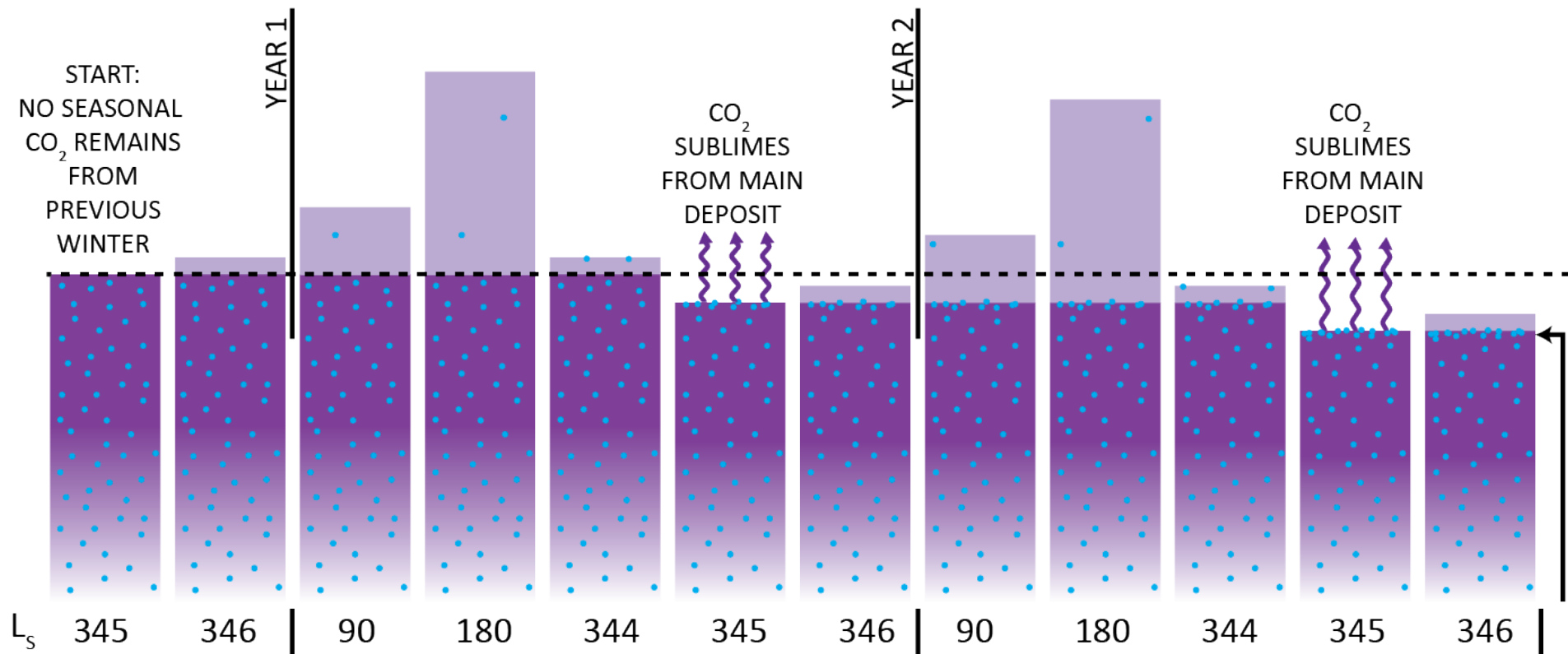
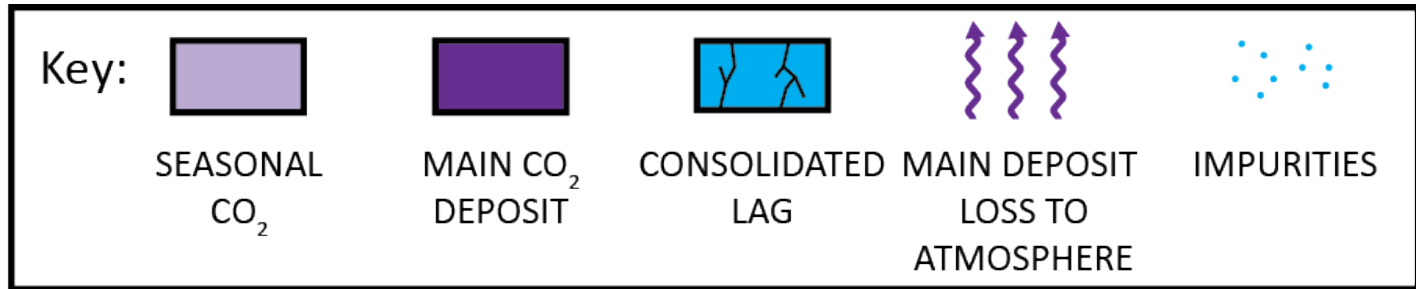


Regions of dark H<sub>2</sub>O layer  
are exposed by L<sub>S</sub> 297

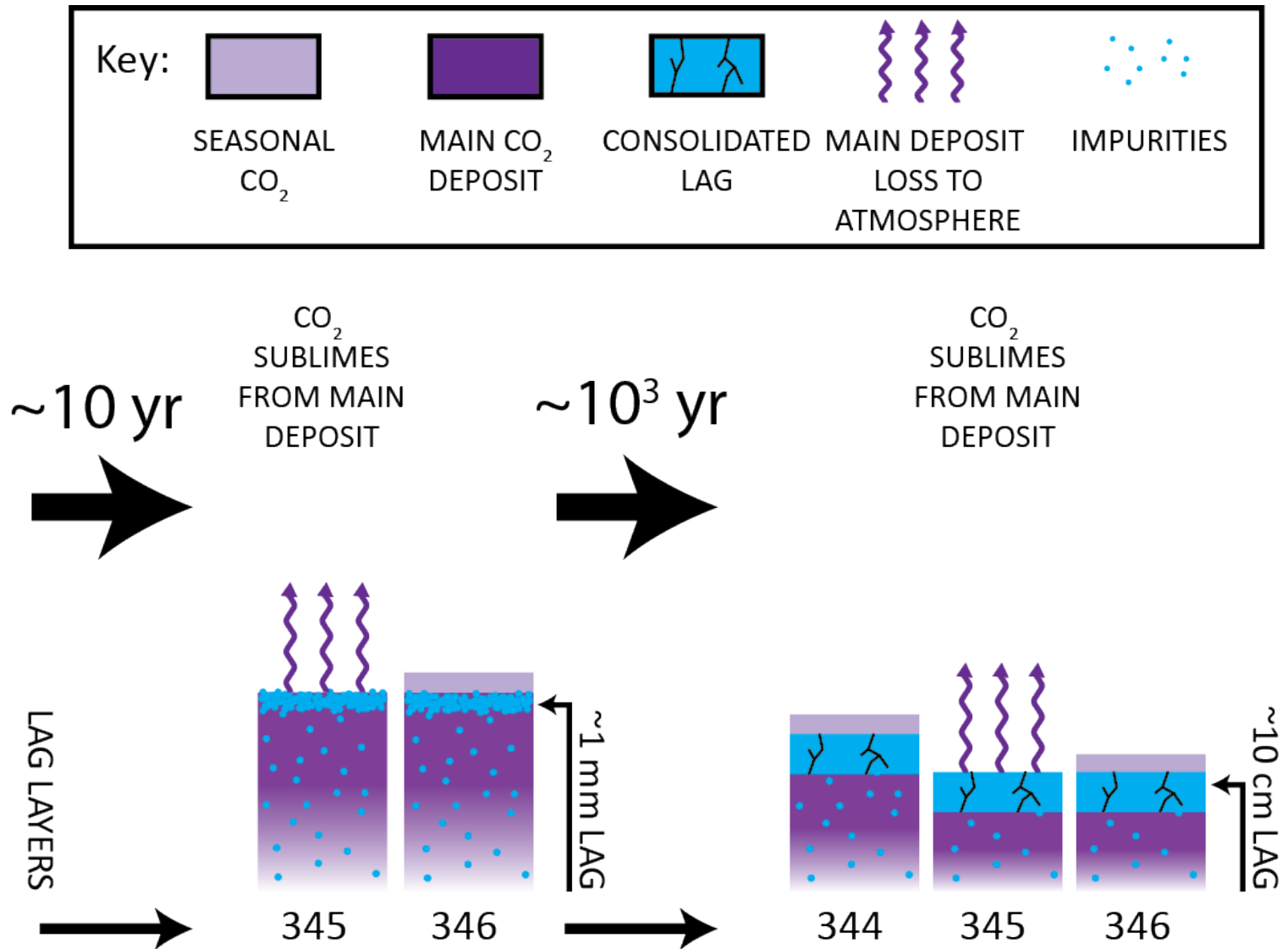
ESP\_013775\_0931

H<sub>2</sub>O Lag Layer and RSPC Formation

# Schematic H<sub>2</sub>O Layer Formation

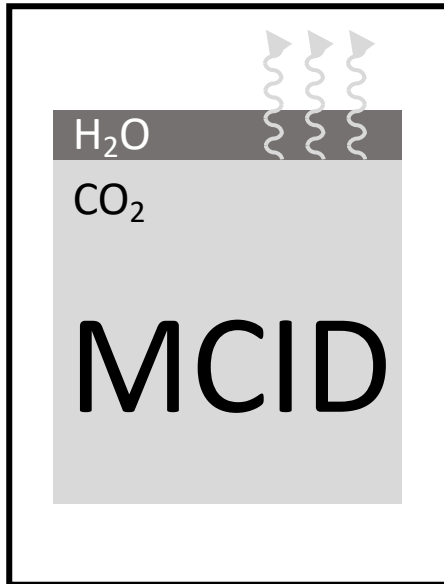


# Schematic H<sub>2</sub>O Layer Formation

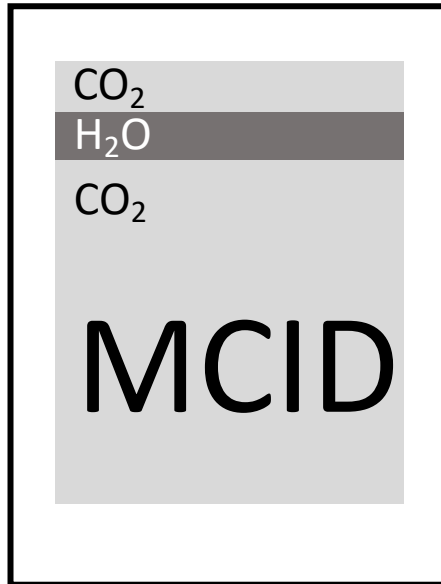


# Is the RSPC a “Fantastic Coincidence”?

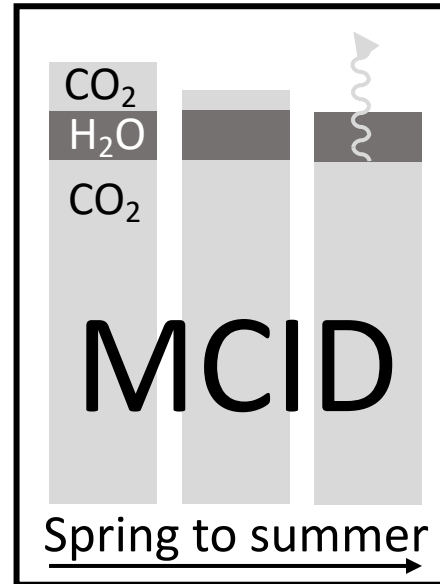
Exposed “scum”  
(H<sub>2</sub>O) dark, less  
volatile, destabilizes  
CO<sub>2</sub> beneath



But then,  
pressure  
increases!  
Restabilizes CO<sub>2</sub>



1D: duration of end-  
summer H<sub>2</sub>O exposure  
can adjust, controlling  
amount of CO<sub>2</sub>  
sublimation



Pitting a  
complication, in 2D  
duration *and* area  
can adjust



Murray and Malin (1973)

RSPC is expected if the CO<sub>2</sub> beneath the H<sub>2</sub>O can exchange mass with the atmosphere; i.e., MCID-atmosphere exchange.

Predictions for  $>10^5$  yr timescales

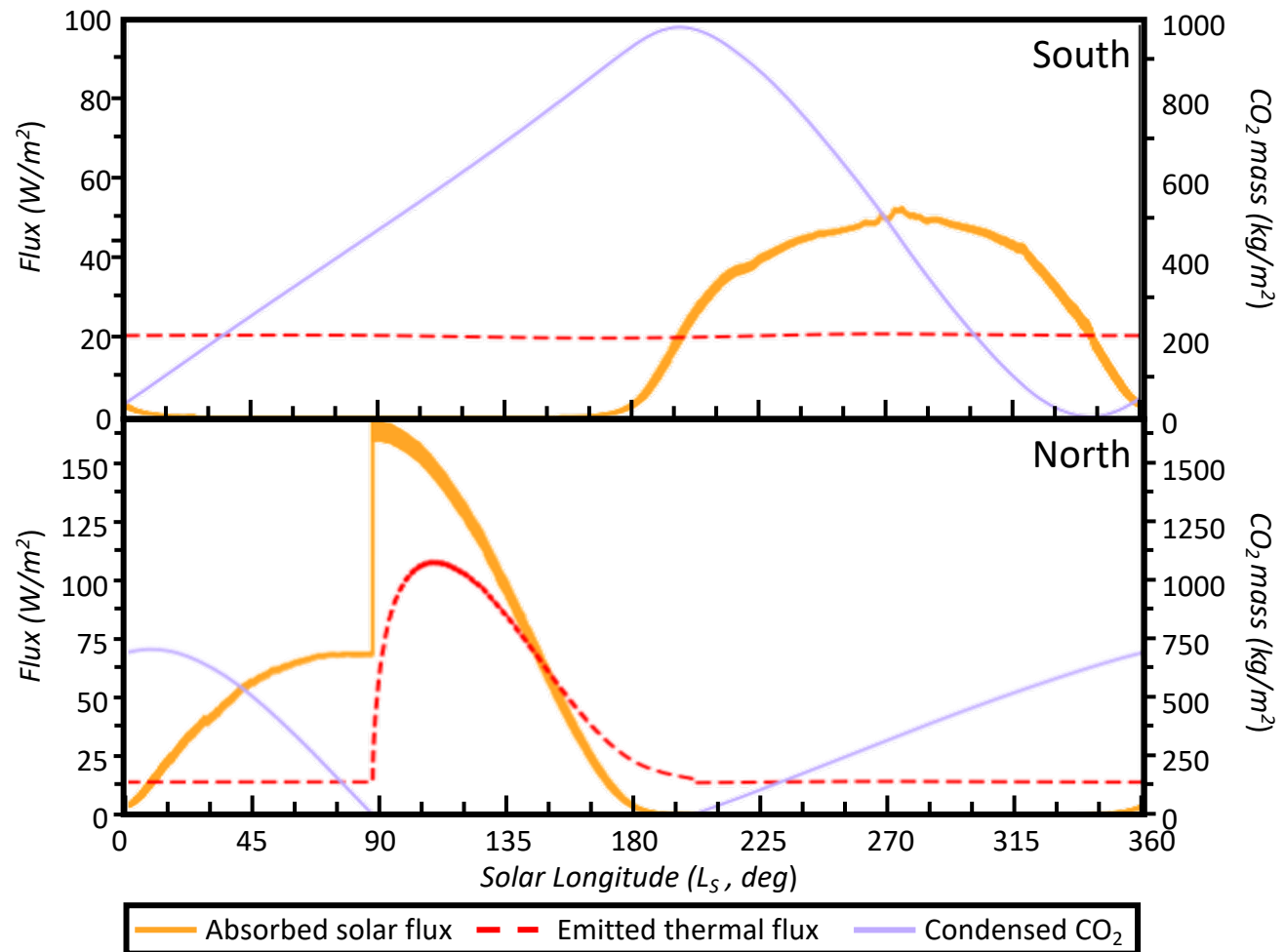
# Why is the permanent CO<sub>2</sub> in the south?

*“There is no reason to suppose a permanent CO<sub>2</sub> southern cap would be at a systematically lower temperature than the northern one.”*

– Murray and Malin (1973)

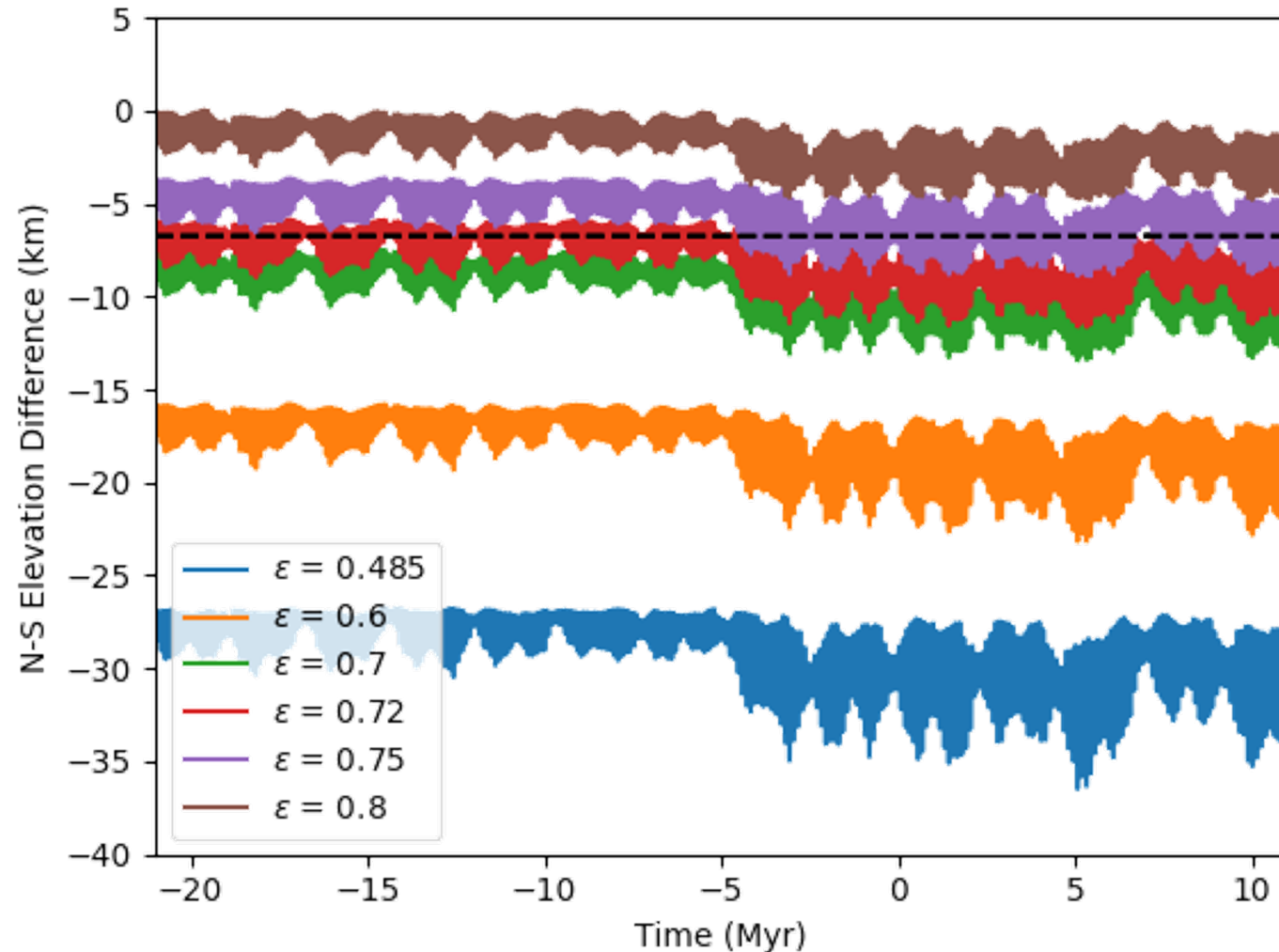
$$\bar{A}_{CO_2} \approx 0.7$$
$$\epsilon_{CO_2} \approx 0.8$$

$$\bar{A}_{CO_2} \approx 0.6$$
$$\epsilon_{CO_2} \approx 0.5$$



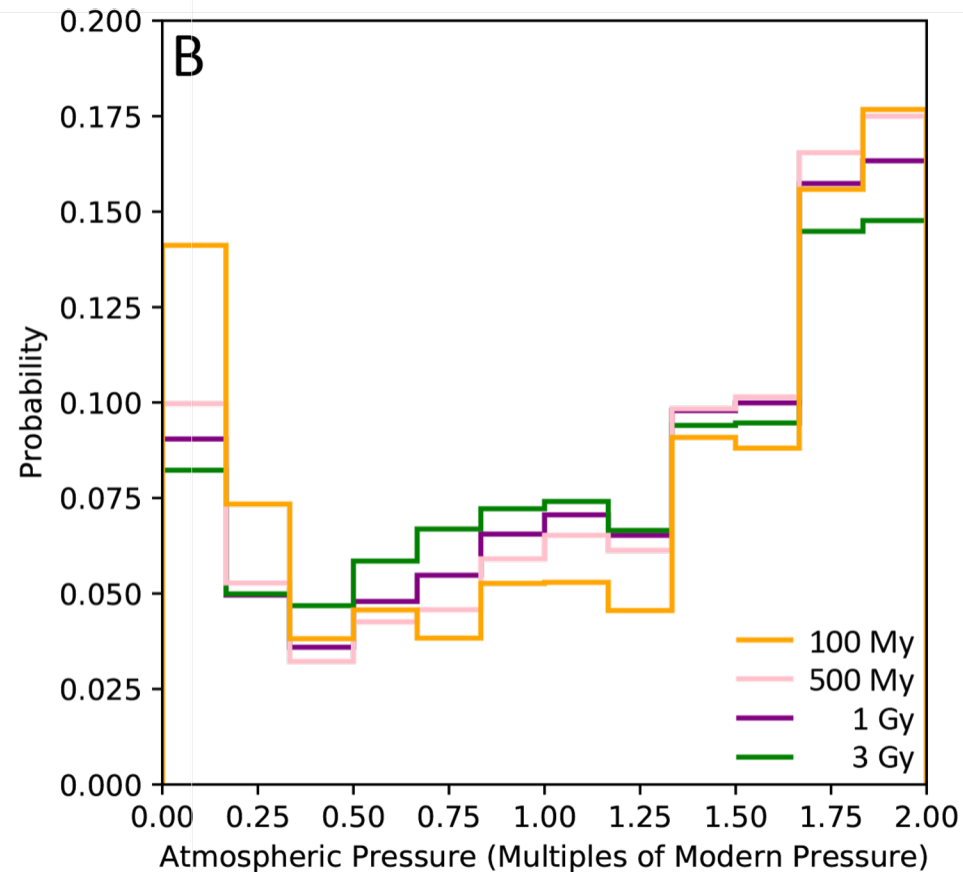
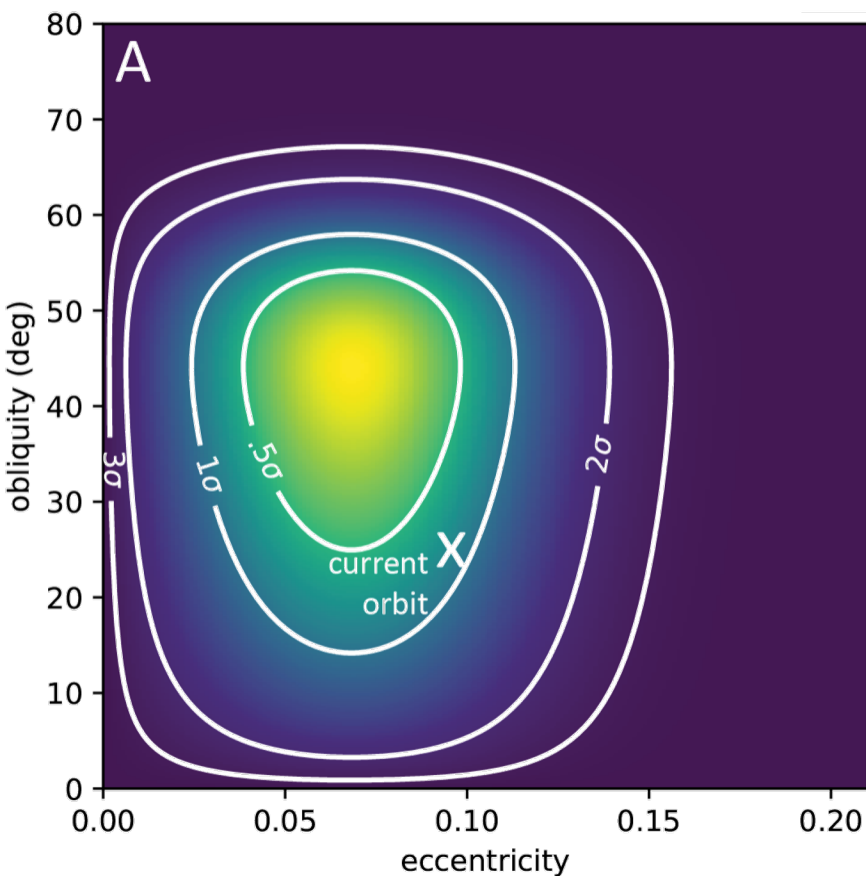
# Will perennial northern CO<sub>2</sub> ever exist?

*“We would expect ... CO<sub>2</sub> residual ice caps to swap hemispheres as the argument of perihelion progresses.” – Guo+ 2010*



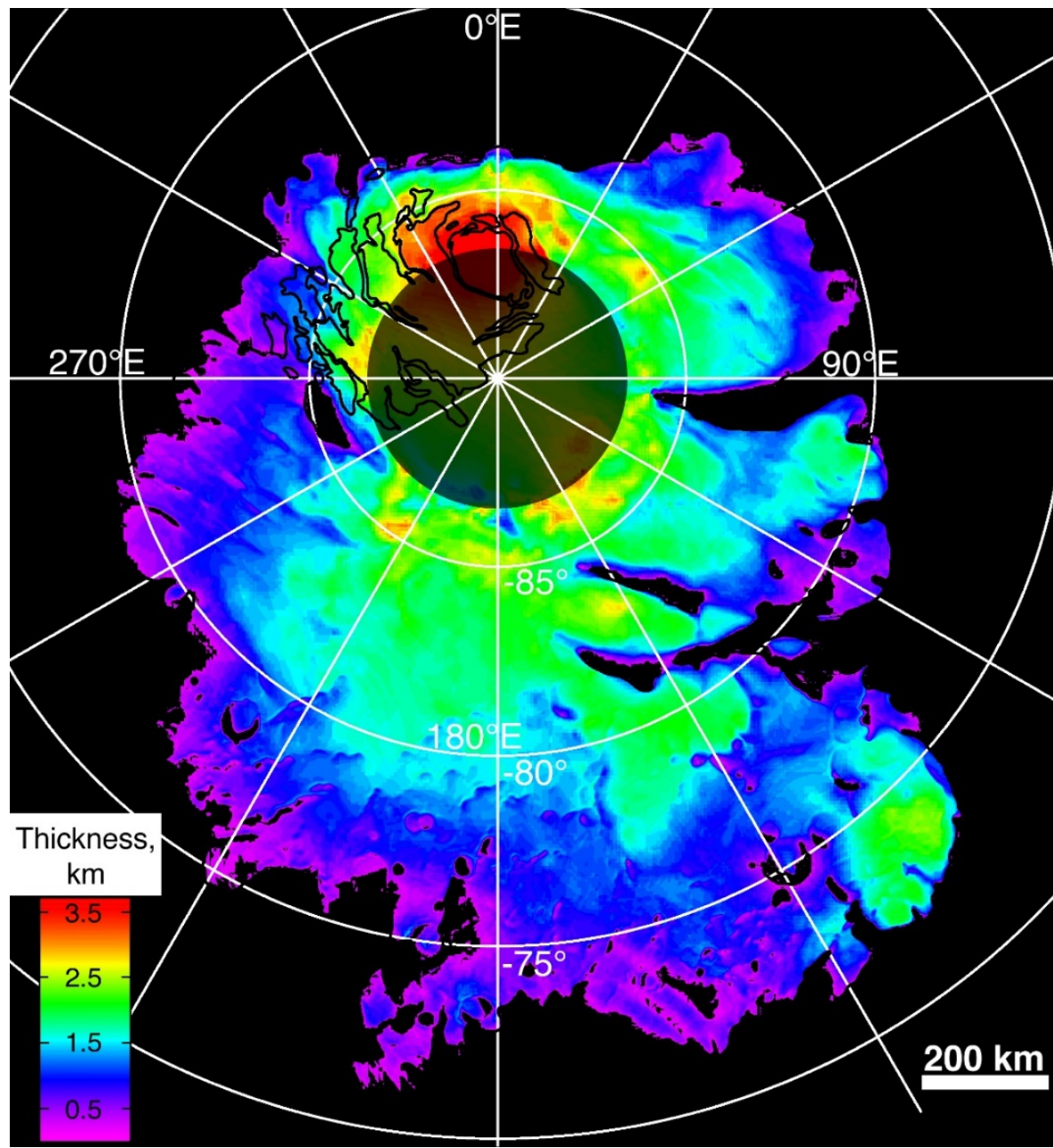
Would require significant changes to  $A_{CO_2}$  and/or  $\epsilon_{CO_2}$

# Long-term pressure history of Mars

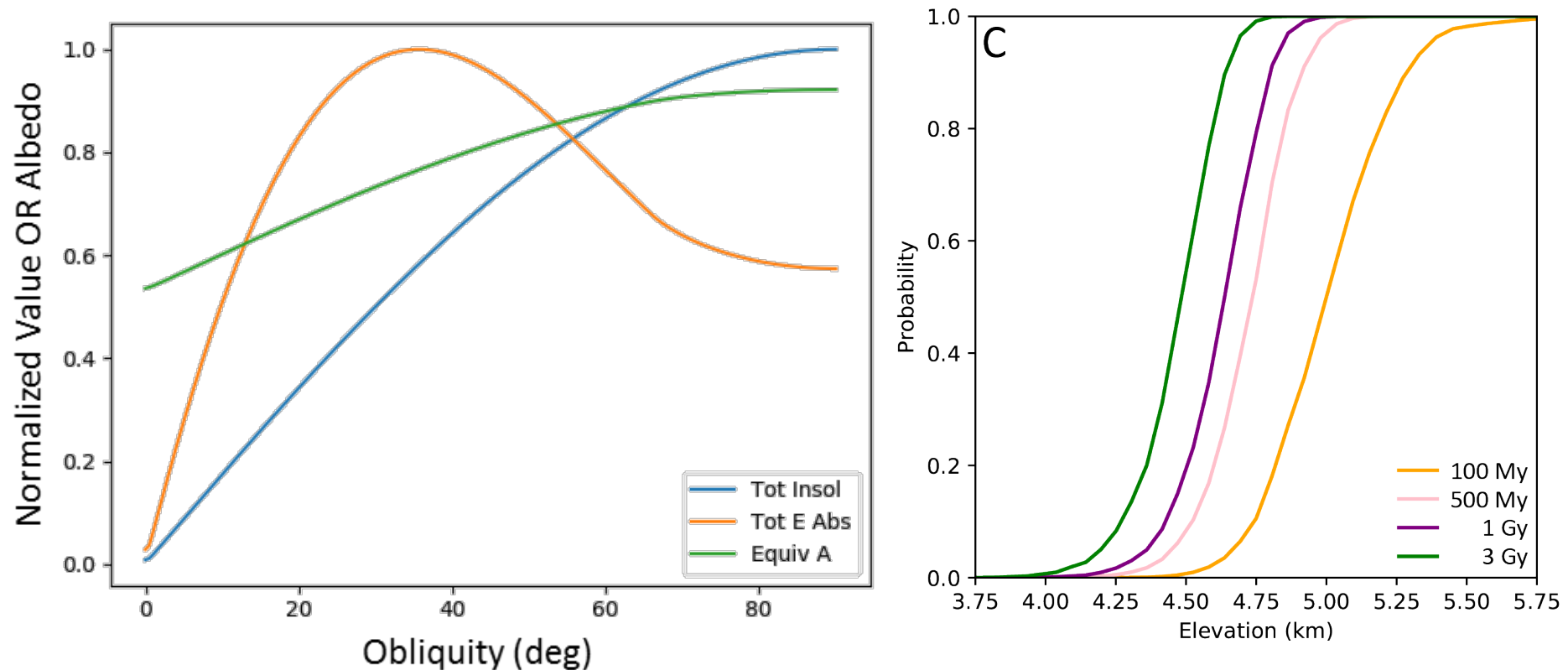


- Median Amazonian pressure:  $1.3 \times$  present
- Interquartile range: 0.7 to  $1.7 \times$  present

# Model consistent with altitude of the MCID



# Model consistent with altitude of the MCID



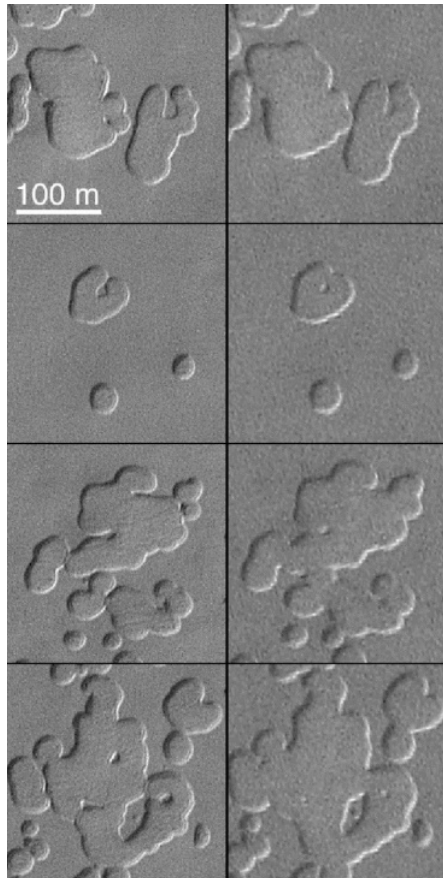
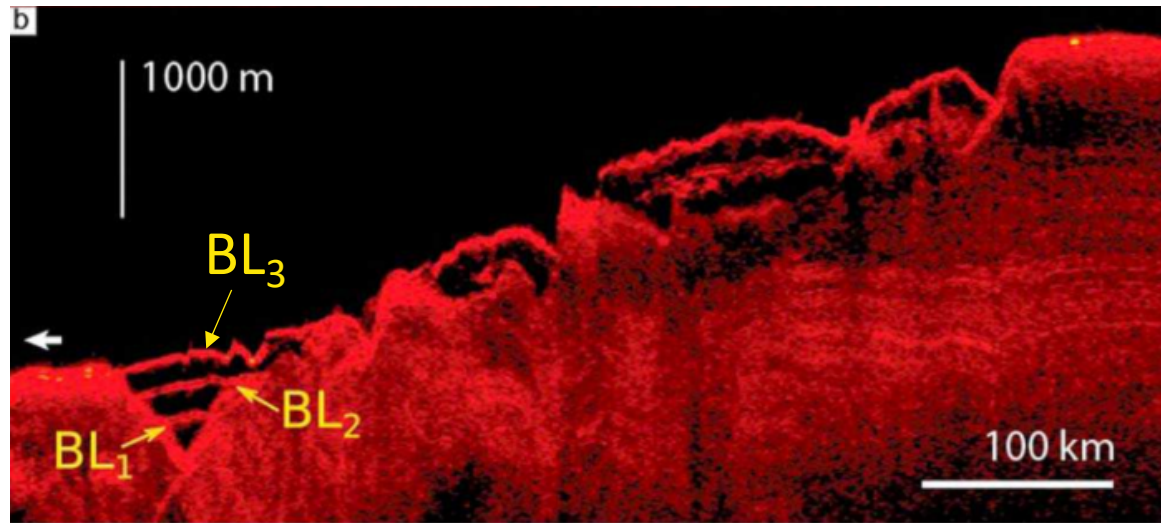
- Maximum absorbed insolation at  $\sim 38^\circ$  obliquity
- Insolation never intense enough to ablate an MCID below  $\sim +4$  km
- SPLD stratigraphy below MCID may record unique climate history

# Conclusions

# Conclusions 1

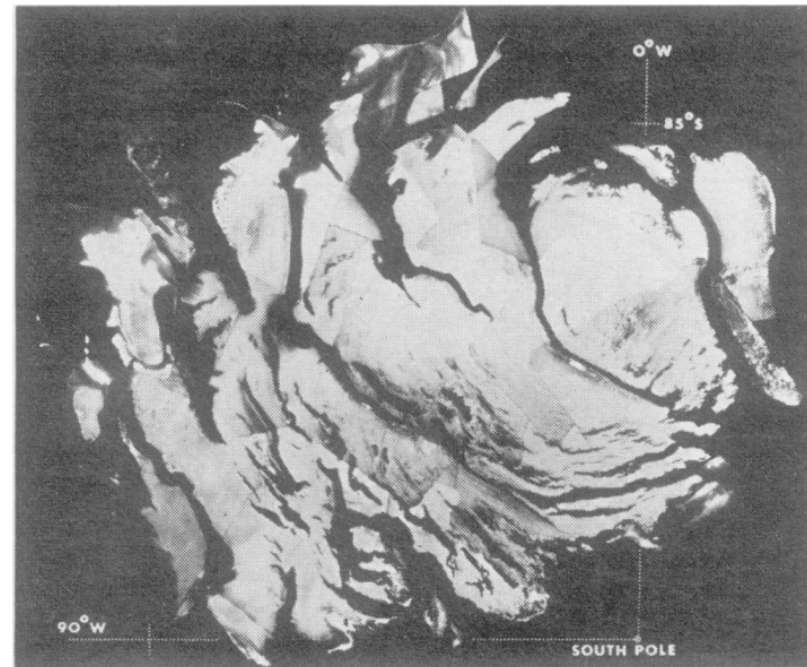
1. How was the massive CO<sub>2</sub> deposit emplaced with its observed stratigraphy?

**Equilibrated co-evolution with the atmosphere, driven by orbital forcing. H<sub>2</sub>O impurities accumulate into lag deposits.**

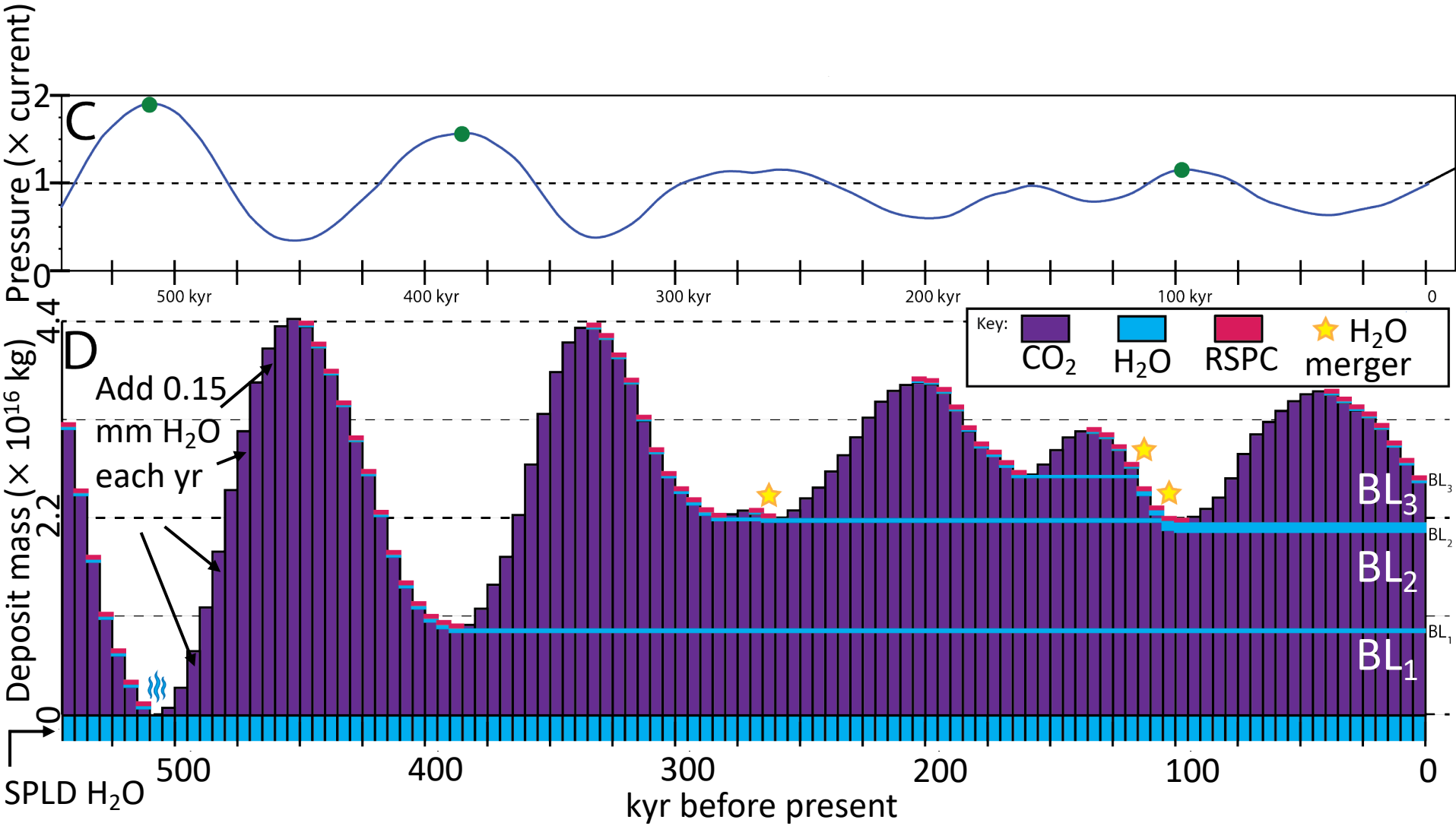


2. Why does the RSPC exist?  
**Negative feedback between surface CO<sub>2</sub> ablation, dark lag exposure, and basal CO<sub>2</sub> sublimation.**

3. Will the permanent CO<sub>2</sub> always be at the south pole (not the north or both)?  
**The albedo/emissivity of the southern CO<sub>2</sub> is higher, overwhelming the lower elevation of the northern cap.**



# Conclusions 2



Questions?